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SOLAR HEATING OF BUILDINGS AND DOMESTIC HOT WATER.(U)
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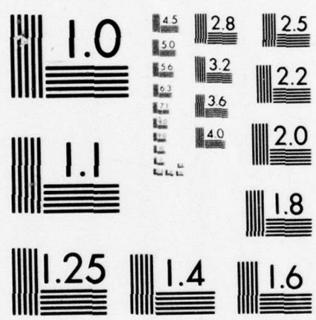

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Naval Construction Battalion Center
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FOREWORD

This document presents necessary guidance for NAVFAC engineers to make preliminary design and cost analyses and prepare specifications for bidders for solar heating systems and domestic hot water.

Widespread adoption of solar heating in Naval facilities at locations where shown to be cost effective could have a significant impact in dollar and fuel savings in the future.

The amount of sun available, the cost of equipment, the cost of available fuels and building heating loads must be considered by station engineers in designing cost effective solar heating systems. This manual brings all these factors together for the first time.

Recommendations or modifications to this manual based on experience in using it are encouraged, and should be submitted to Civil Engineering Laboratory, Code L80, Naval Construction Battalion Center, Port Hueneme, California 93043.

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NORMAN W. PETERSEN
Commander, CEC, USN
Officer in Charge
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1.0 INTRODUCTION

1.1 SCOPE. This report presents design criteria and cost analysis methods for the sizing and justification of solar heat collectors for augmentation of potable water heaters and space heaters. Sufficient information is presented to enable engineers to design solar space and water heating systems or conduct basic feasibility studies preparatory to design of large installations. Both retrofit and new installations are considered.

1.2 RELATED CRITERIA. Certain criteria relating to space heating and domestic hot water (DHW) heating systems appear elsewhere and are listed below.

a. The Department of Defense general requirements are found in the Construction Criteria Manual, DOD 4270.1-M.

b. Cost justification as prescribed by NAVFAC Instruction P-442 is required and is used in the example calculations (Section 4.0).

c. Some portions of Design Manual DM-3 relating to heating and hot-water systems pertain to this manual. These and other relevant sources of applicable criteria are listed below:

Subject	Source
Plumbing Systems	Chapter 1
Heating Systems	Chapter 3
Architectural Criteria	Chapter 5
Electrical Criteria	Chapter 5
Hazards & Safety Precautions	Chapter 5
Insulation	Chapter 5
Structural Criteria	Chapter 5
Central Heating Plant	Chapter 8
Corrosion Protection	Chapter 9
Water Conditioning	Chapter 9
Housing & Bldg. Designs (definitive)	NAVFAC P-272
Weather Data	NAVFAC P-89

1.3 SOLAR ENERGY

1.3.1 SOLAR RADIATION. Energy from the sun is received by the earth as electromagnetic radiation and includes ultraviolet, visible, and infrared components. The atmosphere around

the earth reduces the radiation received on the earth's surface, and is also responsible for the scattering of light which results in diffuse, as distinct from direct, solar radiation. Solar flat plate collectors absorb heat from the diffuse component as well as the direct. Thus, some heat is available on partly cloudy days. Even bright sunlight may be as much as 1/3 diffuse, 2/3 direct. Most of the sun's energy received is in the visible and infrared portions. The amount of sun received at any location depends on the hour of the day, day of the solar year, and amount of clouds present. Solar insolation, I, is measured in Langleys (=3.688 Btu/ft^2). Monthly average and yearly average daily insolation data for numerous Naval installations are given in Table 1-1. In general, the higher the latitude, the less insolation is received on a horizontal surface.

1.3.2 COLLECTING SOLAR ENERGY. Collection of solar energy is based on the very high absorption of radiant energy by dull, black surfaces and on the "greenhouse effect." The latter refers to the ability of glass to transmit visible radiation but prevent the loss of heat from the collector plate which radiates at a relatively low temperature (at infrared frequencies). Glass (or plastic) cover plates are generally used over flat absorber plates to reduce heat loss (see Figure 1-1). The heated absorber plate may have a fluid (water, air or other) pass over it or through tubes attached to the plate. The fluid thus heated may be used to heat potable water, heat spaces or drive an absorption or Rankine cycle air conditioner.

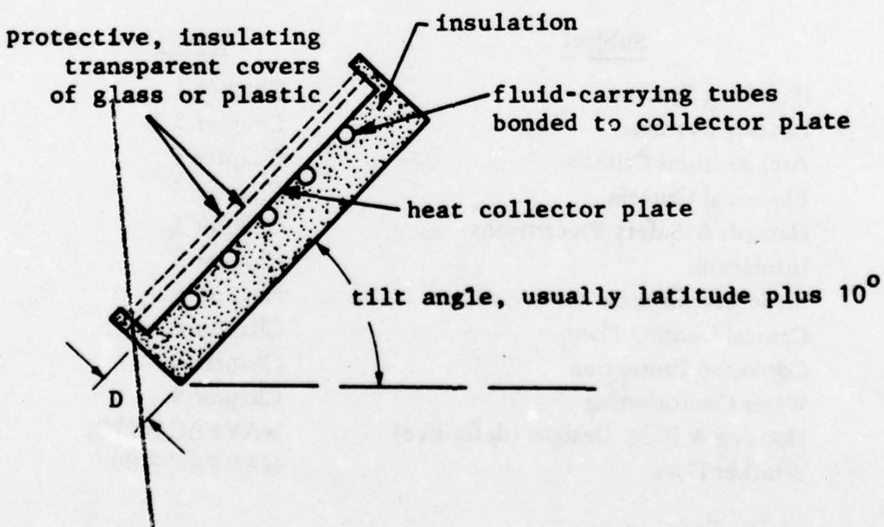


Figure 1-1. Schematic cross section of typical solar heat collector with heavy back insulation and two cover sheets.

1.3.3 ADVANTAGES AND DISADVANTAGES. Solar energy is inherently nonpolluting, provides substantial freedom from the effects of fuel price increases, and saves valuable fossil fuels. Disadvantages are that collectors perform poorly in cold weather, when most needed; and room heat exchangers and industrial unit heaters must be larger than in conventional systems due to the relatively low temperature of heating fluid. The disadvantages may be circumvented by good design; where fuel costs are high enough (as discussed in the examples, Section 4), a solar system will prove cost effective. Solar systems designed for combined heating and cooling will utilize the collector year-around and thus usually will be more cost effective. Cooling design is beyond the scope of this edition of this document.

Table 1-1. Average Solar Radiation Intensities, Langleys/Day (Horizontal Surface)

Radiation Data From	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Annette, AK*	63	113	231	360	457	466	481	352	266	122	59	40	251
Page, AZ*	294	367	516	618	695	707	680	596	516	402	310	243	495
Yuma, AZ	305	401	517	633	703	705	652	587	530	442	330	271	506
Davis, CA*	158	256	402	528	636	702	690	611	498	348	216	148	433
Fresno, CA*	186	296	438	545	637	697	668	606	503	375	241	160	446
Inyokern, CA*	312	419	578	701	789	836	784	738	648	484	366	295	579
Los Angeles, CA*	243	337	446	518	517	594	645	579	505	365	277	228	442
Pasadena, CA	251	333	439	509	569	580	634	599	482	366	271	236	439
Riverside, CA*	271	362	468	526	608	666	652	603	521	400	309	260	470
San Diego, CA	265	343	428	464	493	510	547	499	446	361	284	245	407
Washington, DC*	159	230	320	403	447	558	529	462	367	281	211	147	343
Gainesville, FL*	278	367	445	539	586	544	520	508	444	368	318	254	431
Jacksonville, FL	267	346	423	514	556	525	522	476	383	331	274	230	404
Key West, FL	327	410	490	572	579	543	534	501	445	394	332	292	452
Miami, FL*	343	416	491	544	552	531	537	508	447	389	354	319	453
Pensacola, FL	250	321	405	509	562	568	537	509	430	394	278	224	416
Tallahassee, FL*	274	311	423	483	548	476	544	537	424	353	364	260	416
Atlanta, GA*	228	284	377	484	535	554	538	502	412	350	265	201	394
Griffin, GA*	238	302	388	519	577	580	559	523	437	372	288	210	416
Pearl Harbor, HI*	355	404	438	536	577	562	610	575	536	466	393	349	483
Lemont, IL*	171	232	326	390	497	553	527	486	384	265	157	131	343
Indianapolis, IN*	147	214	312	393	491	547	542	486	405	293	176	130	345
Louisville, KY	164	231	325	420	515	560	550	498	408	303	190	150	360
Lake Charles, LA*	239	304	396	483	554	582	521	506	448	402	296	232	414
New Orleans, LA	237	296	393	479	539	549	502	491	418	389	269	220	399
Boston, MA*	139	198	293	364	472	499	496	425	341	238	145	119	311
Portland, ME*	157	237	359	406	513	541	561	482	383	273	157	138	351
Annapolis, MD	175	243	340	419	488	557	542	469	383	294	189	155	355
Silver Hill, MD*	182	244	340	438	513	555	516	459	397	295	202	163	359
St. Cloud, MN*	170	251	366	423	499	541	555	491	360	241	146	123	348
Cape Hatteras, NC*	244	317	432	571	635	645	629	557	472	361	284	216	447
Sea Brook, NJ*	157	227	318	403	478	522	518	457	385	285	192	139	340
Trenton, NJ	173	244	343	424	491	546	540	469	389	294	195	155	355
Ely, NV*	238	333	464	564	624	708	648	608	519	393	287	220	467
Reno, NV	234	324	449	592	664	714	707	646	532	395	277	209	479
New York, NY*	146	210	312	378	455	526	518	492	361	262	160	128	324
Oklahoma City, OK*	255	317	407	498	540	623	610	588	484	379	284	237	435
Philadelphia, PA	175	242	347	425	493	554	538	465	388	293	191	152	355
State College, PA*	139	202	297	373	467	544	528	454	361	275	155	120	335
Newport, RI*	155	231	330	395	489	538	517	449	380	273	175	141	339
Charleston, SC	250	308	393	517	553	556	523	495	417	349	281	228	406
Nashville, TN	163	240	329	450	517	567	553	494	428	327	217	161	370
Brownsville, TX*	287	336	402	458	556	604	619	555	465	406	284	253	435
Corpus Cristi, TX	262	330	413	474	561	604	629	558	470	408	285	240	436
Dallas, TX	231	307	394	[illegible]	521	595	588	538	458	363	261	221	411
El Paso, TX*	331	432	[illegible]	[illegible]	715	730	670	639	575	462	367	313	536
Norfolk, VA	208	270	[illegible]	477	540	572	550	481	398	310	223	184	382
Seattle, WA*	70	124	244	360	446	471	501	431	310	174	90	59	273
Albrook A. B. Panama*	392	476	525	499	404	336	370	372	448	338	380	420	426
Wake Island*	438	518	570	623	644	648	636	623	587	530	485	399	558
San Juan, P. R.*	429	489	581	607	555	612	643	574	542	495	428	428	532
Taipei, Taiwan	186	216	261	312	381	393	400	412	341	340	296	225	314

* From "World Distribution of Solar Energy," University of Wisconsin Engr. Expr. Sta. Rpt no. 21, by G.O.G. Lor, J. A. Duffie, and C. O. Smith, July 1966.

2.0 SOLAR SYSTEM COMPONENTS

2.1 COLLECTORS. The collector is the most important and one of the most expensive parts of a solar heating system. It must be long-lived and well insulated, yet its cost must be minimized. Collectors of primary interest for space and water heating are of two basic types: liquid and air. Liquids may be water, "heat transfer" oil, or antifreeze mixtures. Heat collector plates are commonly made of copper, aluminum or galvanized steel for liquids, and these materials plus all-glass for air systems. Of these, only copper and all-glass have reported lifetimes greater than 5 years. Collectors using softened water in copper tubes should last over 20 years and air-in-glass, indefinitely. Tubes should be 1/2 inch in diameter or greater for long life and low pressure drop. Typical cross sections of several collector types are shown in Figure 2-1. The better the attachment of tube-to-plate (such as by soldering), the better the heat transfer, but the greater the manufacturing cost. Advances in collector cost reduction will probably be made in the direction of cheaper manufacturing processes. Some collectors not made from tube and sheet may not tolerate Domestic Hot Water (DHW) line pressures. Specifications for pressurized collector circuits should require collectors which will take proof test pressure equal to 150% of expected circuit pressure. Collectors made for heating swimming pools or for use with heat pumps may be inexpensively made wholly of plastic since they are designed for near-air-temperature operation. Metal collector plates should be, and usually are supplied backed with 2 to 6 inches of insulation, sealed in a protective metal, wood or fiberglass pan, and covered with one or more glass or translucent plastic sheets held in a frame, with the spacing between glazes and between glass and plate nominally 1/2 inch or greater. Open flow collectors are an exception with spacings as small as 1/4 inch. Steel enclosure pans should be protected against rust inside due to condensation, such as by rust-resistant paint or asphaltic coating. Glass should be sealed against the weather. Design must provide for thermal expansion of the glass when collector is dry; temperatures up to 400°F can occur. In hot climates, it is important to reduce roof heat load due to collector heat gain in summer; this can be accomplished by venting the space between collector plate and glazes with dampers or removable covers at top and bottom of collector. Heat retention may be improved by use of antireflective coatings on the glass, but they are presently quite expensive, and not recommended. A normal amount of dirt and dust on glass will nominally reduce heat collected by about 5%. Normal rainfall is usually sufficient to relieve this problem. Except for warm climates with high insolation ($I \geqslant 400L/day$), usually two cover glasses are optimum. In warm climates, one glass is optimum. Many plastics have an undesirable transparency to infrared radiation, to which glass is nearly opaque, so the desired "greenhouse effect" is not so pronounced with plastic materials as with glass. However, losses by radiation from the collector are small compared with convective losses due to wind; thus plastics can be employed to reduce breakage and cost, but with some loss in collector performance. Plastics with maximum opaqueness to infrared and maximum transparency to ultraviolet (UV) and visible radiation and with high resistance to UV degradation should be specified. Sizing of collectors will be discussed in Section 3.6. Collectors may be oriented facing to the south or up to 15 degrees west of south in regions with morning fog or haze. If unavoidable, collector can

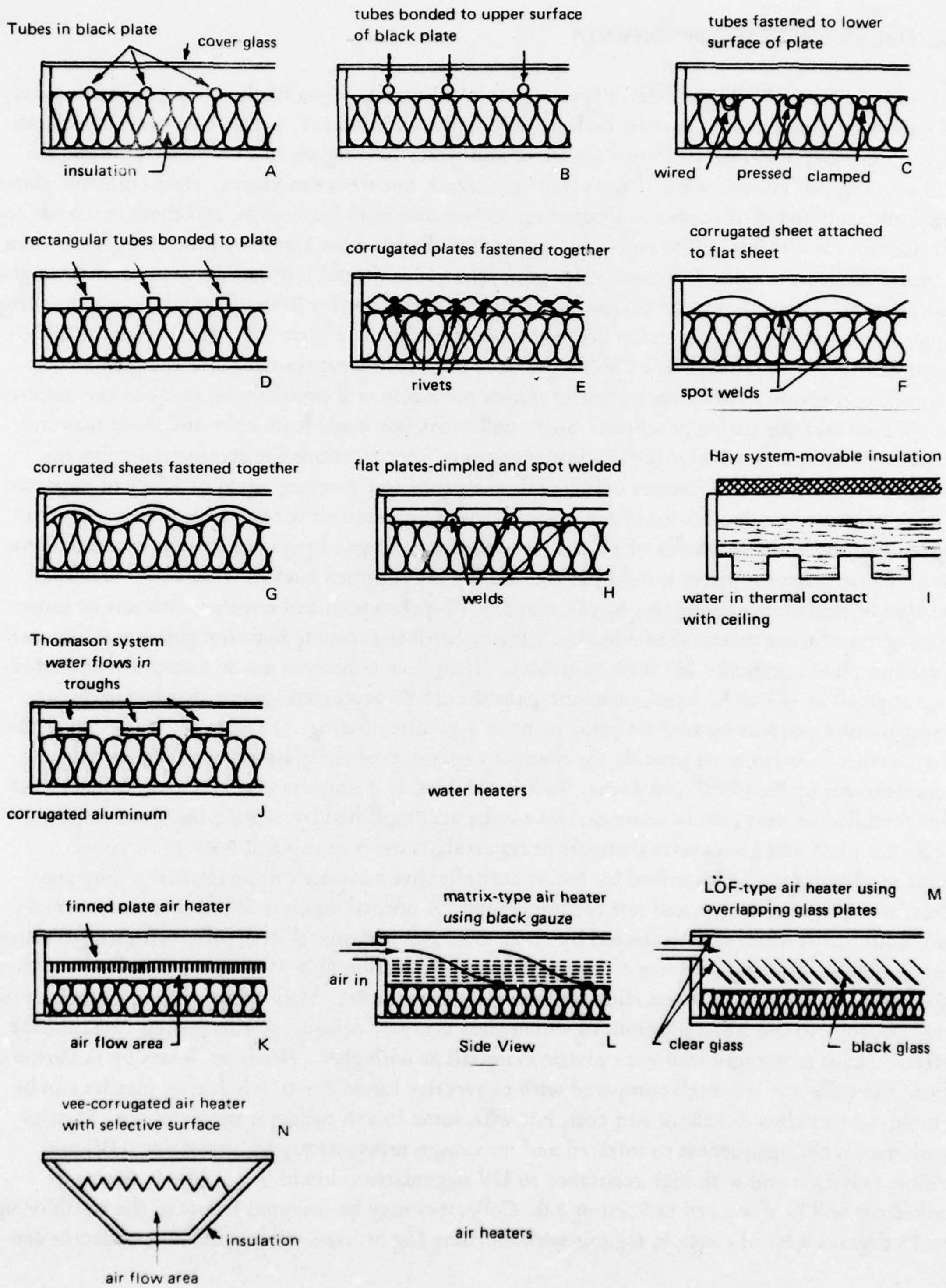


Figure 2-1. Types of solar water and air collectors.

be faced to the east of south up to 20 degrees without excessive losses (<3%). They should be tilted up from the horizontal at an angle equal to the latitude plus 10 degrees for heating purposes. Variation in tilt angle of ±10 degrees will not have a significant effect on collector performance. Liquid and air type collectors each have some advantages. Liquid types are more suited to domestic hot water, the collector area is usually smaller, and more information is available about liquid systems. Collectors for heating air do not require protection from freezing and have minimal corrosion problems, leaks do not cause serious problems, they may cost less per unit area, and are better suited to direct space heating for residences than are liquid types because ductwork is usually present. Wherever this manual discusses liquid collectors, air collectors are included, and cost analyses apply equally to both. The design procedure for air collectors differs, however. Heat transfer oils, while expensive offer freeze protection and some corrosion protection but require heat exchangers for heating domestic hot water, as do antifreeze-water mixtures.

2.1.1 COLLECTOR HEAT LOSSES. Collectors lose heat mainly by convection of wind blowing over their top and bottom surfaces. As may be seen in Figure 2-2, wind has little effect on collectors with two or more glazes. Manufacturers data in Figure 2-2 are based on measured collector efficiencies and reflect nominal heat loss effects. It is most desirable to have efficiency data taken in accordance with Reference 1. Collector efficiency is defined as the ratio of the heat collected to the insolation (I) falling on the surface. Efficiency is usually plotted versus ΔT or $\Delta T/I$

where $\Delta T = T_c - T_a$

$T_c = T_{avg} = (T_o + T_i)/2$

T_o = temperature of fluid leaving collector

T_i = temperature of fluid entering collector

T_a = ambient air temperature

Plate temperatures are always higher than fluid temperatures, on the order of 1°F for water-copper collectors, and more for other materials. Honeycombs installed between plate and glazes have been tested; their effect is to reduce natural convection and re-radiation inside the collector-glass cavity, but not enough is presently known about their cost for them to be recommended here.

2.1.2 SELECTIVE SURFACES. Some collectors are manufactured with a black coating which absorbs very well the high frequency incoming solar radiation and which emits low frequency infrared radiation poorly. This is a highly desirable combination of properties for a collector. The absorptance should be 0.9 or higher and emittance may be 0.1 or lower. Such experimental coatings are expensive and are approximately equal in effect to one cover glass. Thus, a selective

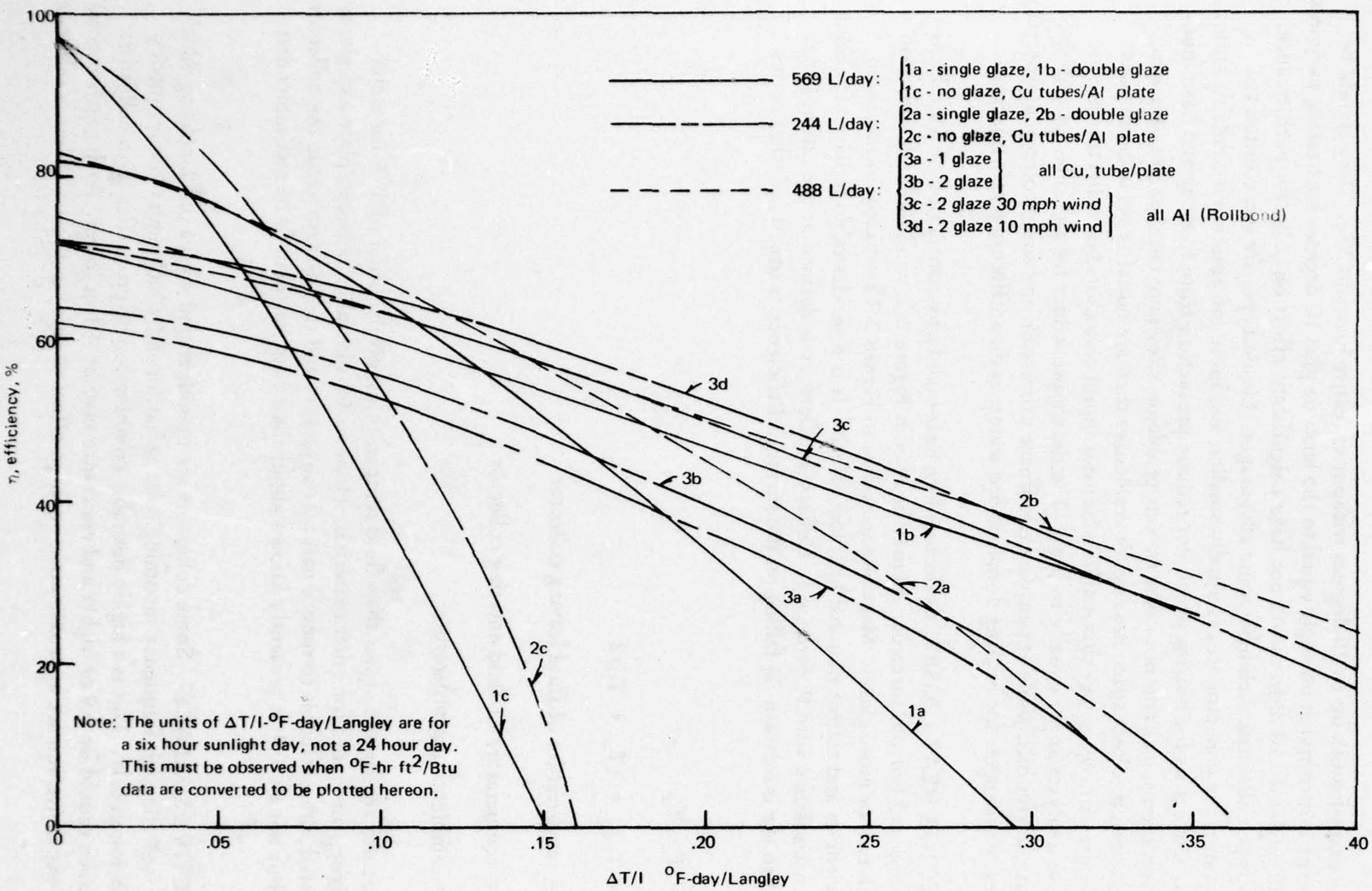


Figure 2-2. Solar collector efficiencies.

coating plus one cover glass may be expected to be about equal in efficiency to a collector with two cover glasses and a flat black painted surface. Electroplated black nickel, chrome, copper or anodized aluminum are common types of selective coatings. Cost of such coatings may now be greater than an extra sheet of glass, but in the future costs will probably be less than the glass. The stability of black nickel, chrome and aluminum in the presence of moisture has not yet been proven. Long-term stability in the presence of moisture or other expected environmental factors (salt air, etc.) must be included in specifications for selective surfaces.

2.1.3 COLLECTOR CONNECTIONS. Water flow through nonhorizontal collectors should always be against gravity, except in trickle-type collectors. Usually this means water inlet to the collector at the bottom, and outlet at top. Care must be taken so that equal flow goes to all tubes. If manifold ΔP is large, then center tubes will get little flow. The simplest design to analyze is one wherein all collectors are connected in parallel. This results in the largest volume of water per collector area being heated. Temperatures will be adequate if designed as described here. Higher temperatures than in the parallel arrangement may be obtained with parallel-series connections, but at the expense of reduced efficiency and greater cost. These high temperatures are not usually required for hot water and space heating. Very large installations may merit computerized system studies considering two or three stage series connection heating, using low temperature, inexpensive collectors for the first stage, as in Figure 2-3 (Reference 2).

2.1.4 FREEZE PROTECTION. Water in liquid collectors requires freeze protection in most climates. An automatic system which drains all exposed water lines and collectors may be employed. Otherwise, an antifreeze must be used, but this necessitates a heat exchanger for potable water heating.

2.2 ENERGY STORAGE AND AUXILIARY HEAT. Since effective sunshine occurs only about 5 to 6 hours per day (in temperate latitudes), and since heating and hot water loads occur up to 24 hours a day, some type of energy storage system is needed when using solar energy. Figure 2-4 depicts energy supply and demand for a typical three day period. The design of the storage tank is an integral part of the total system design. Although numerous storage materials have been proposed, the most common are water for liquid collectors and rock for air. These have the advantages of low cost, ready availability and well known thermal properties.

2.2.1 DOMESTIC HOT WATER (DHW) STORAGE. Domestic hot water systems (without space heating) may use a lined, insulated, pressurized tank similar to the conventional water heater with safety valves and controls, as in Figure 2-5. Auxiliary heat (gas, steam, electric) may be added directly to this tank on cloudy days; 100% backup capability is needed in the auxiliary for reliability (but oversizing is not necessary).[a] Warm water should enter and leave

[a] In large installations justifying a system study, it may be desirable to take a small risk based on, say, a 0.99 probability of the estimated number of cloudy days, and call for a larger storage volume, with less than 100% backup auxiliary heat source.

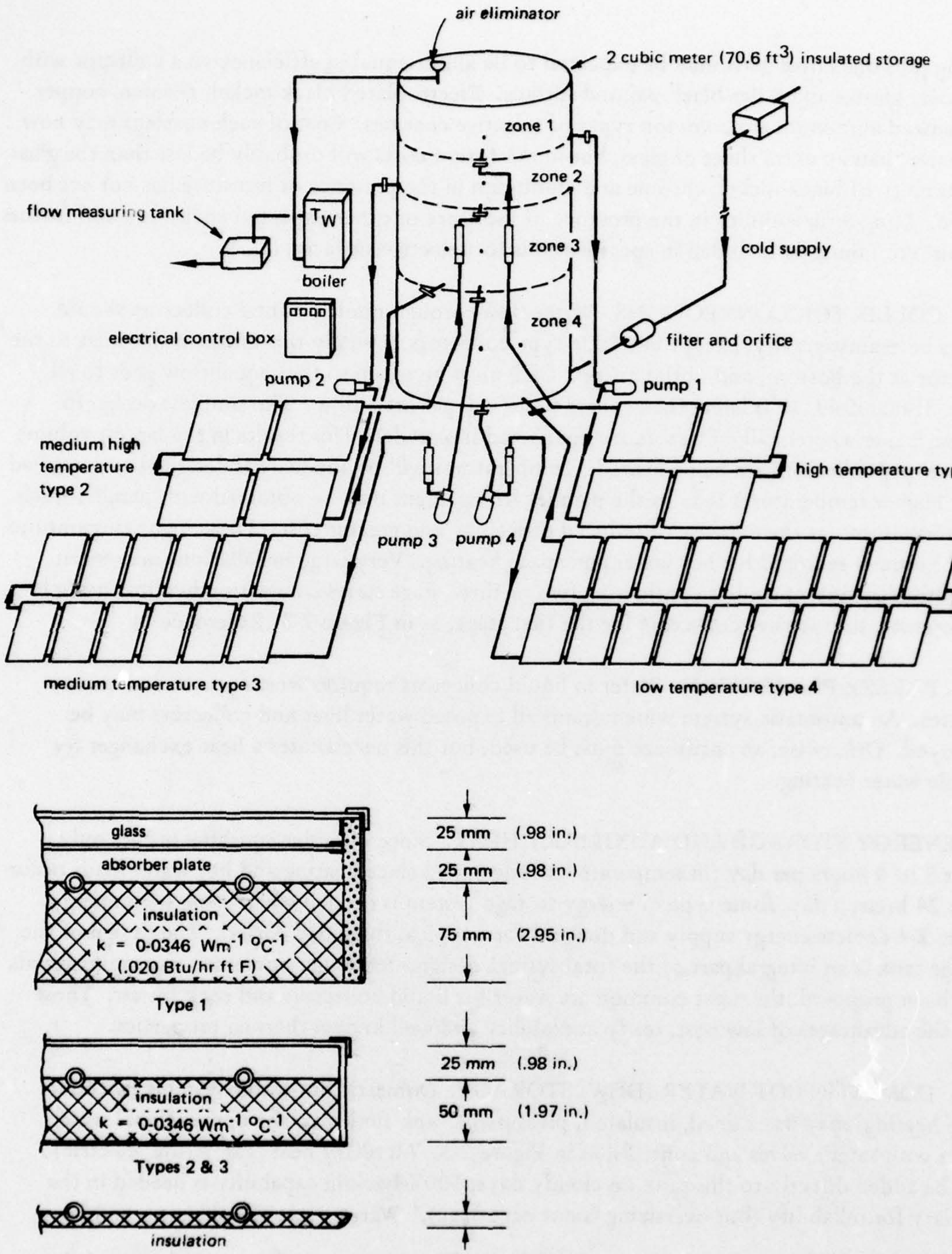
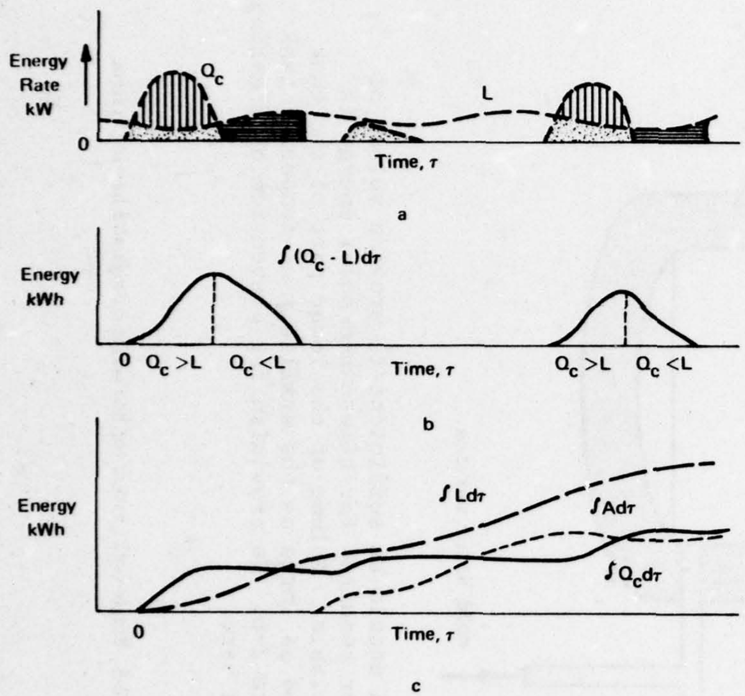


Figure 2-3. DHW system with four stages.

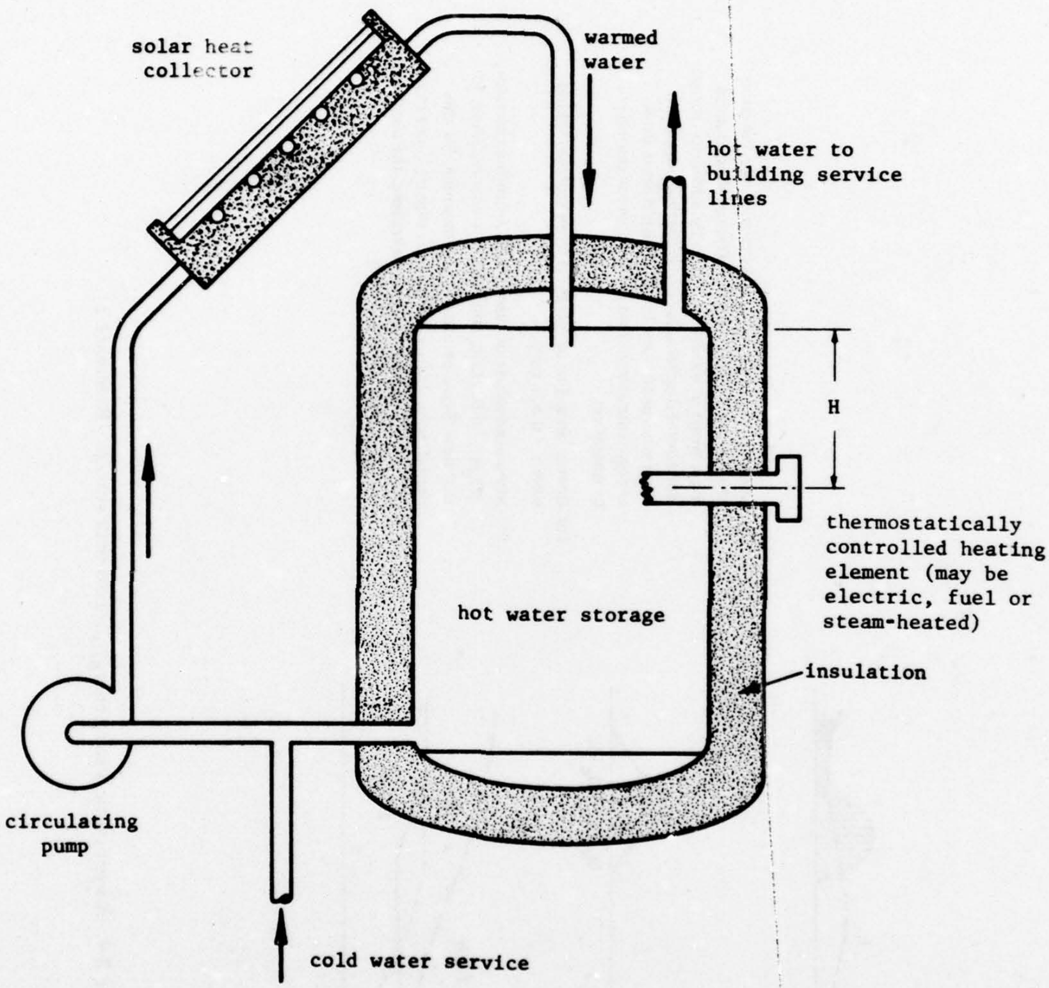


(a) Collector useful gain Q_c and loads, L as a function of time for a 3-day period. Vertical shaded areas show times of excess energy to be added to storage. Horizontal shaded areas show energy withdrawn *from storage to meet loads. Dotted areas show* energy supplied to load from collector during collector operation.

(b) Energy added to or removed from storage, taking time $\tau = 0$ as a base.

(c) Integrated values of: useful gain from the collector, $\int Q_c d\tau$; *load, $\int Ld\tau$; and auxiliary energy, $\int Ad\tau$, for* the same 3-day period. In this example, for this period, solar energy collected is slightly more than half the integrated load, and exceeded the auxiliary energy supply. (Reference 2)

Figure 2-4. A hypothetical solar energy process with storage. (Reference 3)



Height H should be sufficient to provide volume of hot water required for times when solar energy is not available. Volume of the lower part of the tank should be as large as the auxiliary or tempering tank of Figure 2-6. No provision for prevention of freezing is shown here.

Figure 2-5. Single-tank system for hot water storage and heating system.

top of tank, and cold, the bottom, to suppress convection. Contrary to conventional practice, stratification is desirable in solar storage tanks so that hottest water is not tempered, and coldest water goes to the collectors. The single tank system will usually be specified for new single residences. Larger systems may be justified in using the scheme of Figure 2-6. Use of two tanks insures that when hot water from the first (tempering) tank is available, the auxiliary heat will not come on; also, less total fuel will be used to bring the smaller second tank up to temperature. Finally, colder water will enter the collector in the two-tank arrangement than with the single tank, increasing collection efficiency slightly. A promising variation of the latter arrangement involves using an unlined (or inexpensively lined) unpressurized (so less expensive) first tank, with the domestic supply heated in a coil in the first tank which then feeds the second tank. Freeze and corrosion protection are easier in this design than with the pressurized tank, since antifreeze can be added to nonpotable water in the first tank. Another advantage of the two tank arrangement is that it is well suited to retrofits, even in single residences, since the second tank (the water heater) is already there. When storage tanks are to be custom made, a calculation of heat loss against expected fuel cost inflation will probably justify doubling the thickness of insulation (up to 6 inches) around the storage tanks (compared with usual thickness of 2 inches). Hot water inlets to storage tanks should be carefully designed to minimize mixing in the tank. Sizing of tanks will be discussed in Section 3.6. Tanks may be made of steel, concrete, fiberglass, copper, or other suitable material. Table 2-1 gives approximate comparative costs for tanks of various materials. All storage tanks for liquids should be located so that if they leak, damage to the building will be prevented. The cost of housing the tank or burying it must be included in the total cost of the solar heating system. Buried tanks must be protected from ground water, and buoyant forces resisted. Tank must be reasonably accessible for repairs. In very mild or warm climates, outdoor location may be feasible.

Table 2-1. Storage Tank Costs[a]

Type of Installations	Cost Per Gallon for Tank Size (gal) —						
	80	120	300	500	1,000	2,000	4,000
Steel, unlined, nonpressure[b]			$0.80	$0.50	$0.45	$0.40	$0.35
Steel, unlined, 100 psi[b]	$2.00	$1.55	1.05	1.00	0.95	0.90	0.85
Steel, glass lined[b]	2.50	3.20	2.60				
1/8-inch fiberglass liner for unlined tank				0.85	0.75	0.55	0.40
Polyethylene tank, nonpressure	2.00	1.80	1.50				
Fiberglass tank, nonpressure	2.80	2.20	1.60	1.50			
Concrete				0.75	0.60	0.55	0.45
6-inch insulation and sheath	1.30	1.20	1.00	0.90	0.60	0.45	0.40
Normal installation above ground including pad	0.75	0.75	0.75	0.70	0.50	0.35	0.25

[a] All prices, $/gal, June 1975, Los Angeles area.

[b] Includes supports and fittings; add $0.10/gal for phenolic lining of unlined tanks.

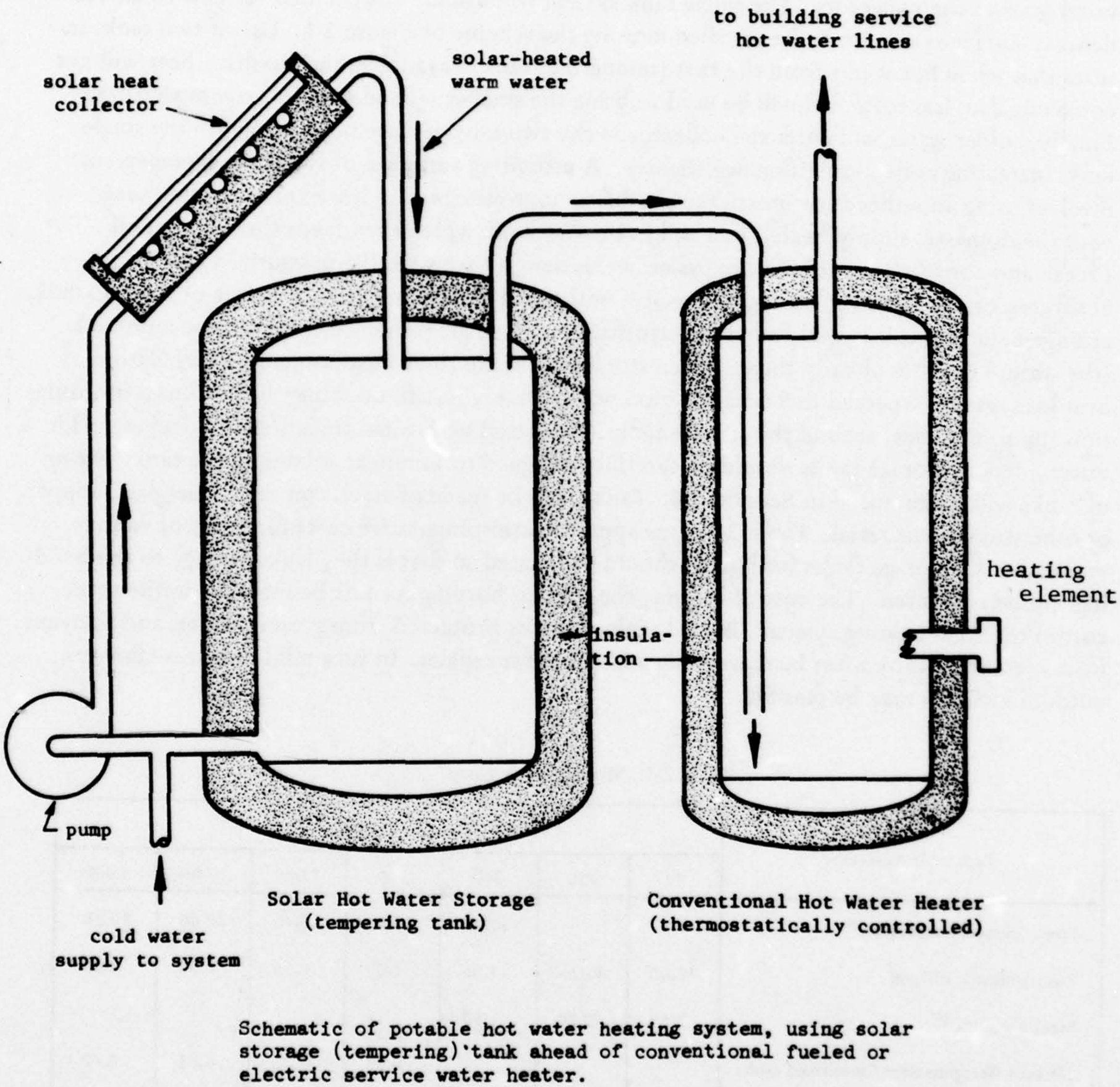


Figure 2-6. Schematic of potable hot water heating system, using solar storage (tempering) tank ahead of conventional fueled or electric service water heater.

2.2.1.1 THERMOSYPHON SYSTEMS. The thermosyphon system for DHW uses the principle of natural convection between a collector and an elevated storage tank. Its advantage is that no pump is required. The bottom of the tank should be mounted about two feet higher than the highest point of the collector. Thermosyphon systems are widely sold commercially for single family dwellings and have operated successfully for many years in the Middle East and many other parts of the world.

2.2.2 SPACE HEATING AND DOMESTIC HOT WATER (DHW). Design of the space heating system, if a retrofit, will depend on the existing system. Water-to-air heat exchangers may be placed in existing ductwork, in which case, an unpressurized, unlined tank may be used as in Figure 2-7. Domestic hot water may be preheated (tempered) by a coil in this tank. Homes with a hydronic heating system can utilize the hot water directly. Auxiliary heat may be added directly to the tank or added in a second stage tank, or a separate furnace (using same ductwork) may be used; 100% backup capability is needed for reliability (but oversizing of furnace is not necessary)[b]. The arrangement of Figure 2-7 may be used for building cooling by using the collector at night to radiate heat to the sky and storing cool water for use during the day. An unglazed collector is superior to glazed collectors for heat rejection. If a two-stage collector (with first stage unglazed) is employed, both heating and cooling are improved, at some increase in cost. Here, the domestic hot water requirements must be met with fuel or a separate collector or a dual-use collector (heating during day, cooling at night) must be arranged. A calculation of these tradeoffs must be made. Air systems may use an air-to-water heat exchanger and use water for storage, or, more commonly, a storage cylinder filled with stones (from 1- to 3-inch diameter) is used. Rock provides very desirable temperature stratification. Design should emphasize minimum pressure drop through the rock bed (length/diameter $\approx$ 1.0). Maintenance-free, the rock bed may be put beneath the building if ground water is not a problem; insulation around the bed is recommended. Air flow is usually in one direction for storing heat, and the reverse direction for use of stored heat. Note that in contrast to water storage, heat cannot be added to and removed from the rocks at the same time. Dampers and ductwork must be designed so that heat from the collector goes either to load or to storage, depending on load, or heat flows from storage to the heating load. See Reference 3 for design of packed bed rock storage.

2.3 SYSTEM CONTROLS. System controls must turn on a circulating pump or blower to the collector only when the sun is providing heat. Differential thermostats are commercially available to turn on the collector pump only when the collector plate temperature is "x" (say, 10°F) degrees hotter than the storage tank bottom temperature. If the building load requires heat, then other controls must direct other pumps or blowers to provide heat from the storage tank to the load. The latter control is the conventional thermostat. The same room thermostat may control the auxiliary heater; however, a delay timer or a two-step room thermostat must be

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[b] See footnote *a*, p 9.

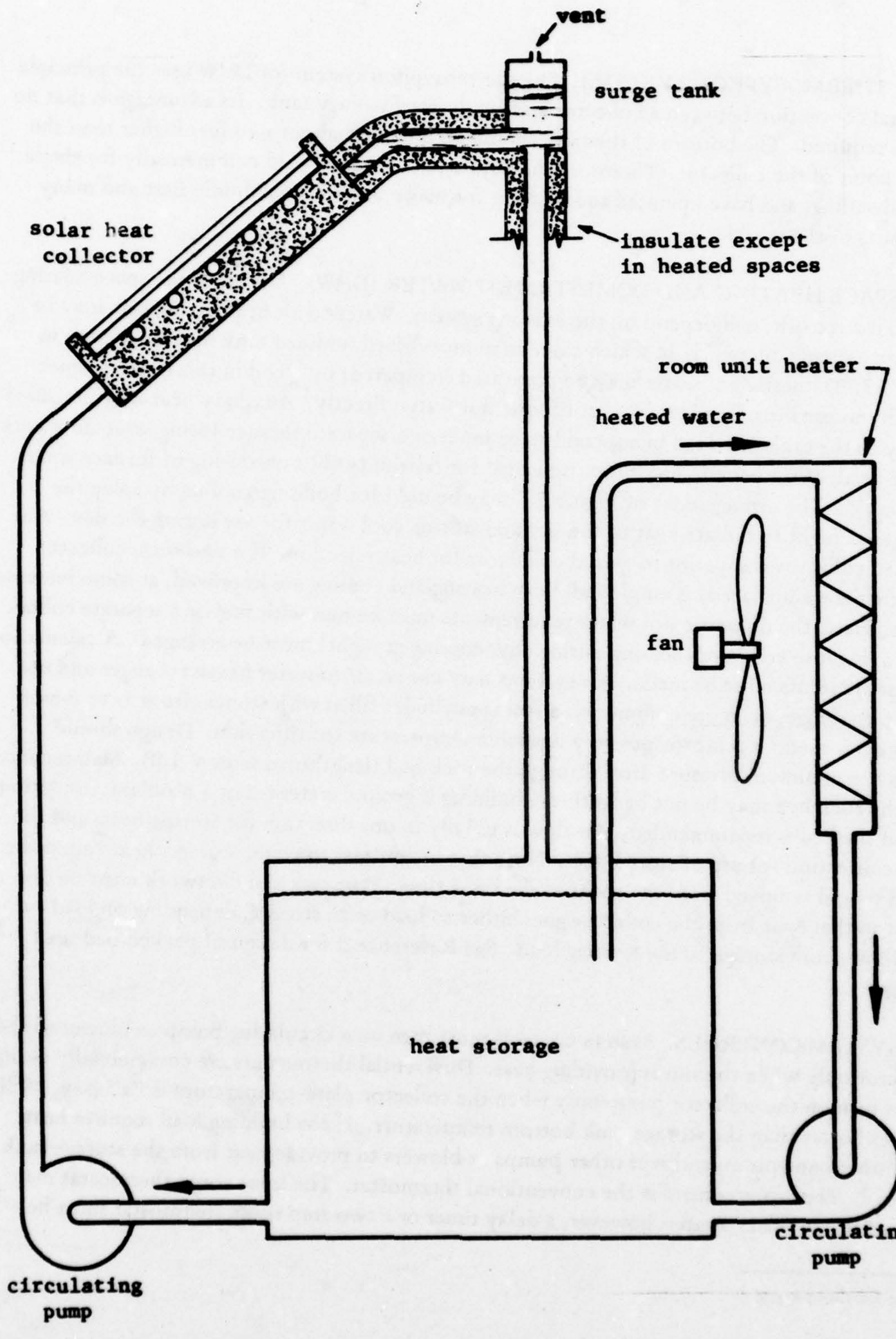


Figure 2-7. Minimum heating system, showing relationship of collector, storage, and room unit heater.

incorporated into the auxiliary heater control circuit so that the auxiliary heat will not come on if heat is available from storage. Figure 2-8 illustrates a typical control schematic. Ten minutes has been suggested as a typical time delay before auxiliary heat comes on.

2.4 ARCHITECTURAL CONSIDERATIONS. Solar collector arrangements should be studied to facilitate blending collector panels into the architecture of new or existing buildings. Figures 2-9 through 2-15 are examples of various solar designs. Shade trees must be so located as not to cast shadows on the collector. Other structures such as chimneys which can cast shadows should be carefully located to avoid shading of the collector. Experience of Florida installers indicates that if collectors are placed directly on the roof, the life of asphalt shingles under the collector may be reduced by up to 50%. This suggests that a small space should be left between the collector and the roof (although this has not yet been tested), or the collector should be built into the roof. In the latter case, the design must provide for simple glass replacement.

2.4.1 REDUCTION OF HEAT LOSSES. Reduction of heat losses is usually one of the most important steps in the design of a solar space heating system. It almost always costs less to super-insulate a building to reduce losses than to provide additional solar collector area to provide the extra heat. Installing 12 or more inches of insulation in the attic, insulating existing walls by injecting nonflammable foam (one manufacturer claims 30% reduction in total heat loss at cost \$0.75/ft^2 floor area), multiple glazing, and weatherstripping should all be evaluated for cost effectiveness versus a larger solar system. If the solar-augmented system is found to be cost competitive with a conventional system on a life cycle cost basis, then the cost effective amount of insulation will be the same for both the solar and conventional systems. Thus the solar system should not be charged for the cost of insulating the house.

2.5 OTHER CONSIDERATIONS

2.5.1 MAINTENANCE AND ACCESSIBILITY. Maintenance of glass will be minimized if vandalism can be reduced. Collectors on flat-roofed buildings may be shielded from the ground by a skirt around the roof perimeter. Locating the collector in the backyard area of residences rather than on a street-facing roof reduces probability of vandalism. Double strength glass for top surface is recommended in hail areas, and also provides protection from small stones. Still more protection is offered by a screen of 0.5-inch mesh stretched several inches above the collectors, but with some loss in collector efficiency (15%). Collectors and mounts must withstand expected wind and snow loads. Collector design should allow for rapid replacement of glass covers. Pumps, pipes, and controls should be reasonably accessible to allow repair or replacement. Water pumps should be located so that leakage does not cause serious damage.

2.5.2 PIPING, PUMPS, VALVES. Piping should be designed for low pressure drop. All exposed piping should be well insulated with approved weather-resistant insulation. Dielectric unions should be used at connections between dissimilar metals. Rubber hose used for connections must be of a high temperature type. Copper pipe is preferred to galvanized steel due to its longer

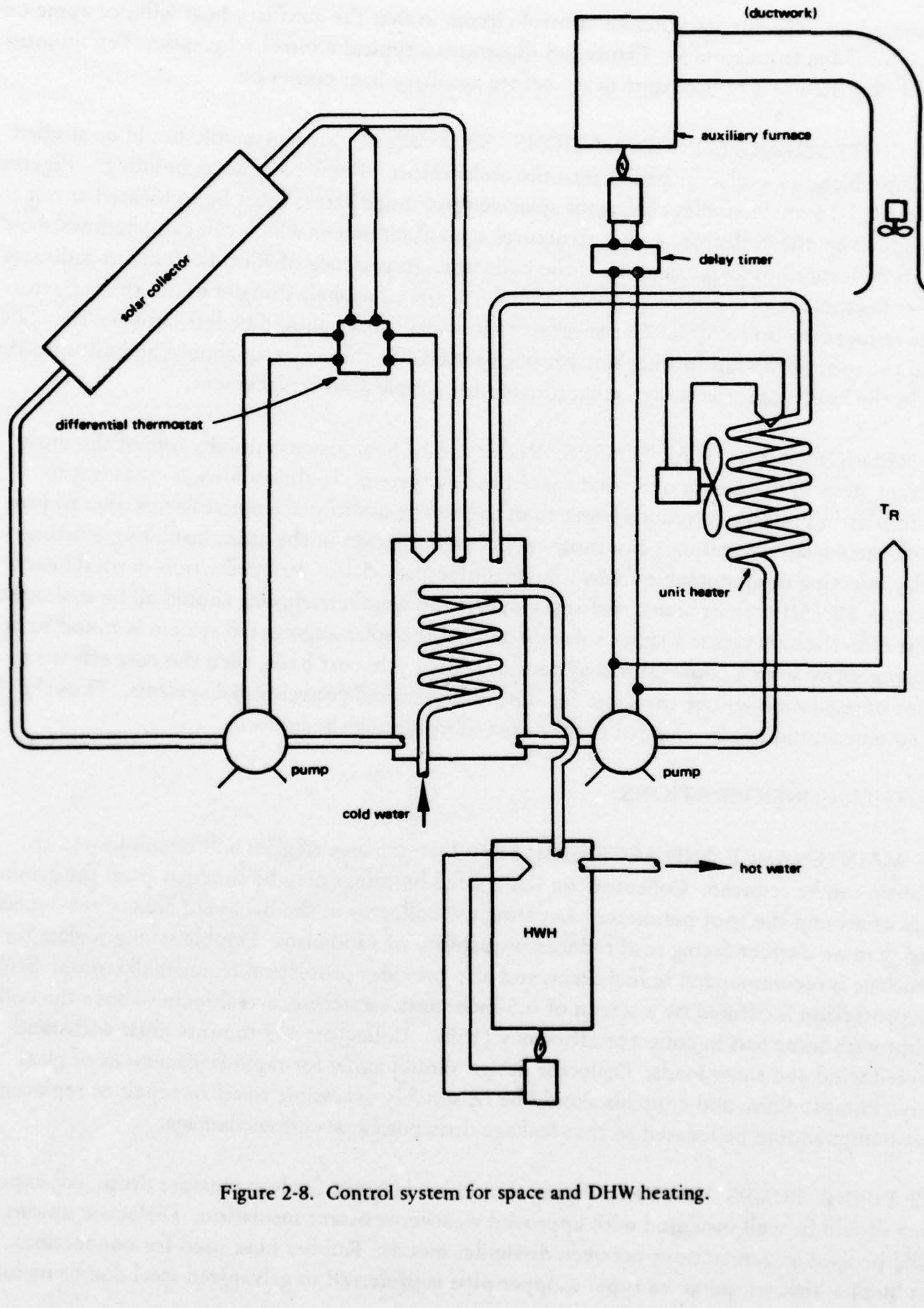


Figure 2-8. Control system for space and DHW heating.

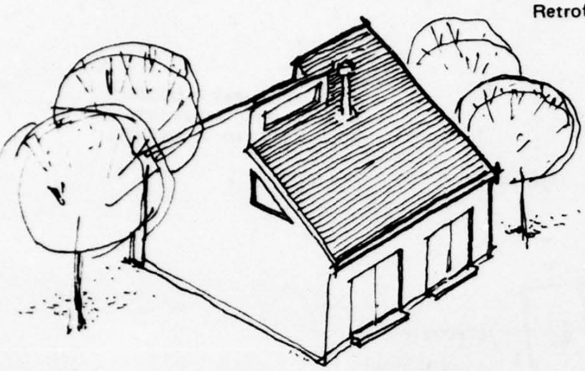
Retrofit Air Heater

Concept
Greatest conservation impact = existing housing inventory

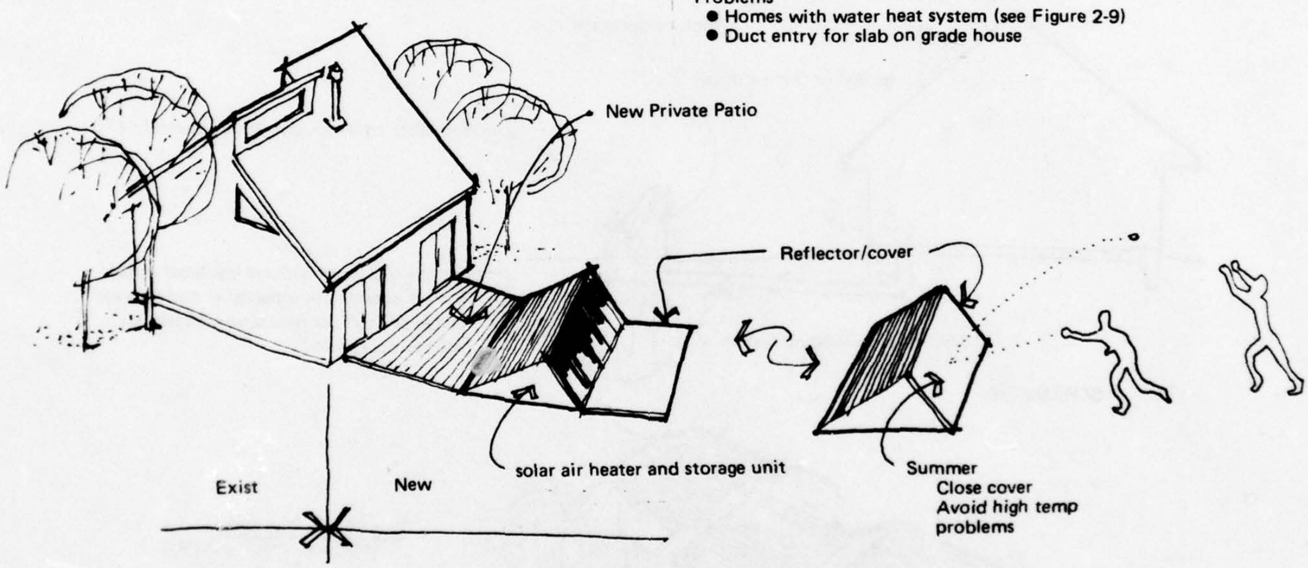
Approach
- Minimize in-building work
- Utilize (supplement) existing heating equipment
- Keep collector free of building
  - orientation
  - structure
  - landscape
  - occupants
- Dual use of collector i.e., provides privacy etc.

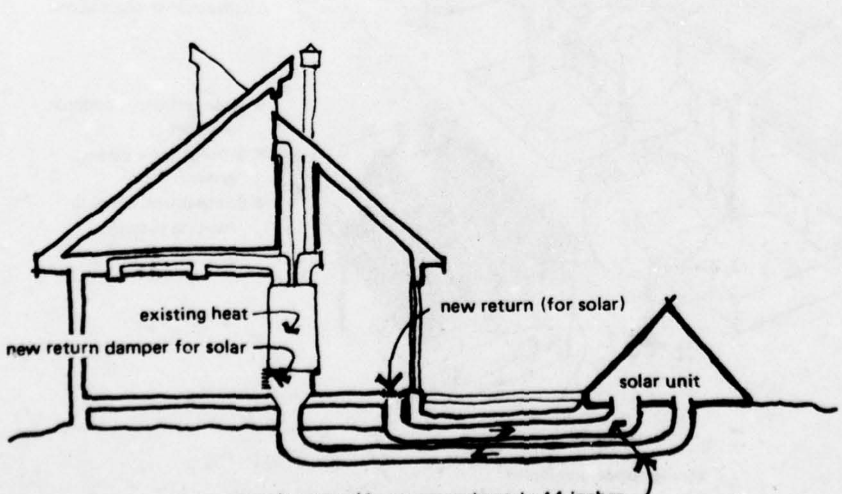
Advantages
- Exist heat system retained
- Any orientation (solar)
- Minimum disruption of existing

Problems
- Homes with water heat system (see Figure 2-9)
- Duct entry for slab on grade house



EXISTING RESIDENCE
crawl space
warm air heat





Solar Applications

Figure 2-9. Solar applications—retrofit air-type space heater.

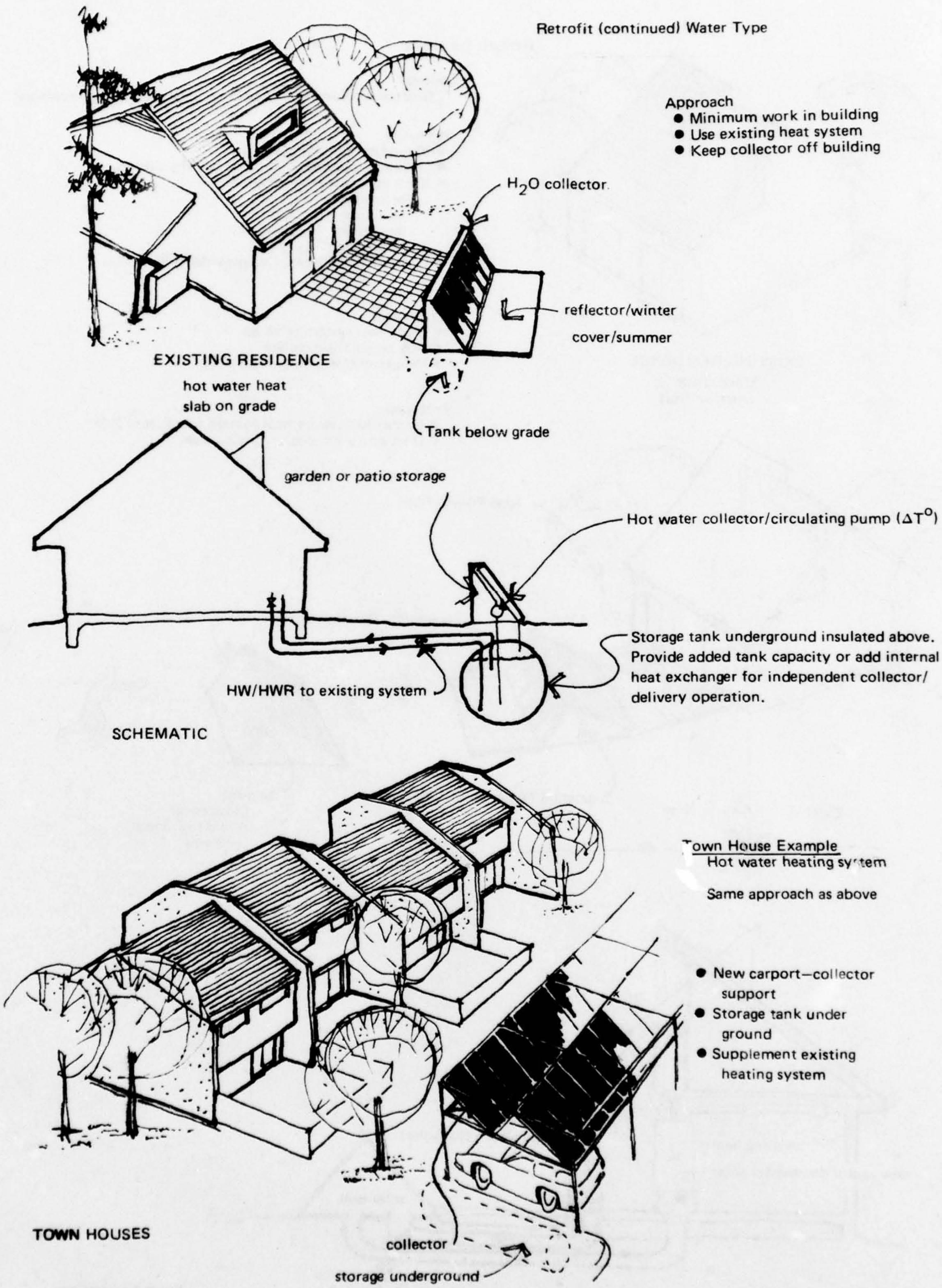
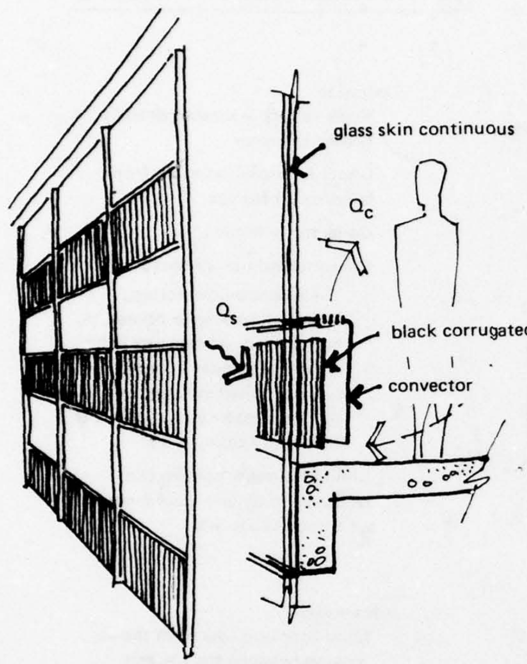


Figure 2-10. Solar applications–retrofit water-type space heater.



ODEILLO OFFICE (FRANCE)
South wall

New construction - office
passive system

Approach
air collector for buildings
used during day only

Operation
natural (convective)
transfer of solar Q to building Q

Advantages
- Operative during building use period - thus no storage
- Simple, no moving parts
- Effective in ideal climate

Problems
- night operation

Figure 2-11. New construction (office)—passive system.

Thermosyphon DHW System

wall (vertical) collector close cover each night-avoid drain requirement. Adjust reflector for season.

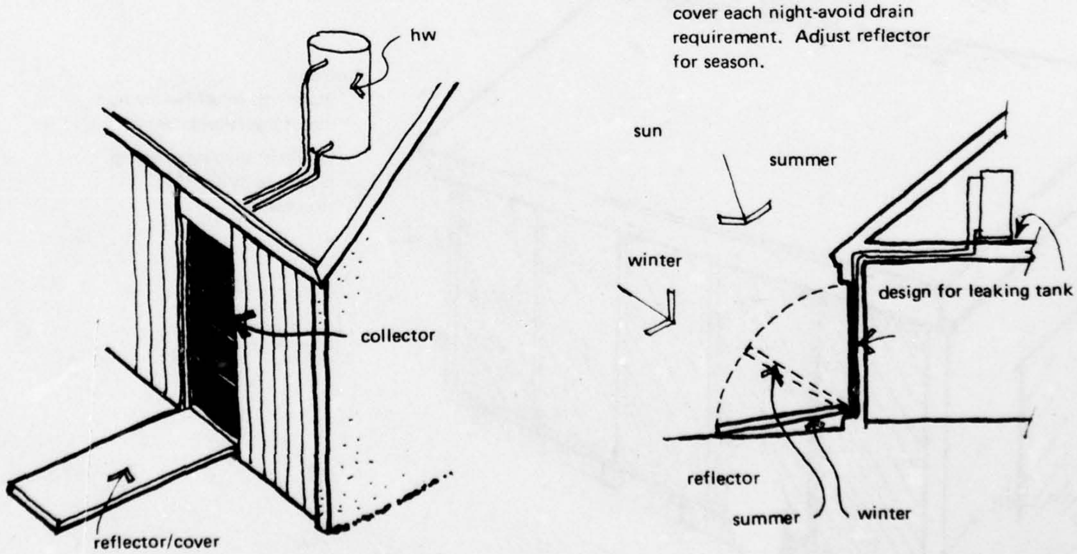
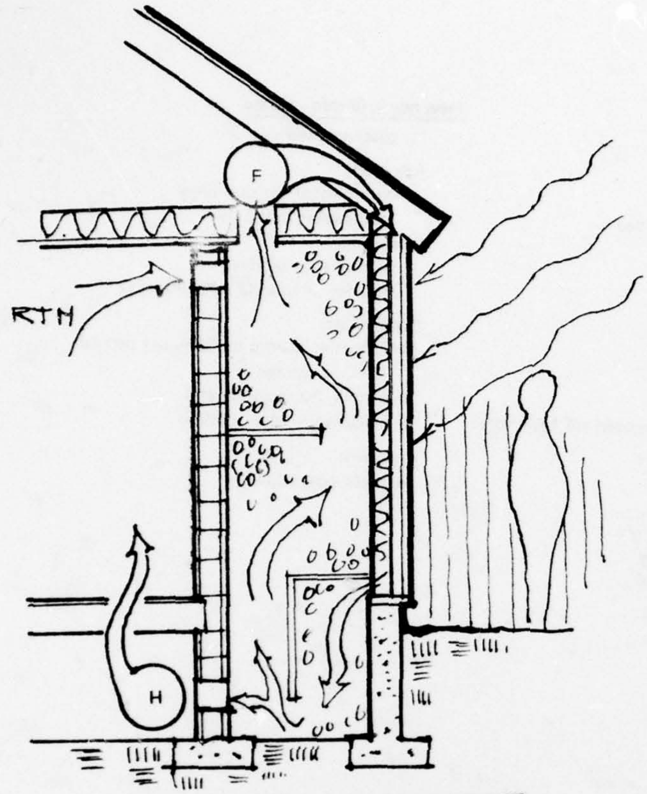
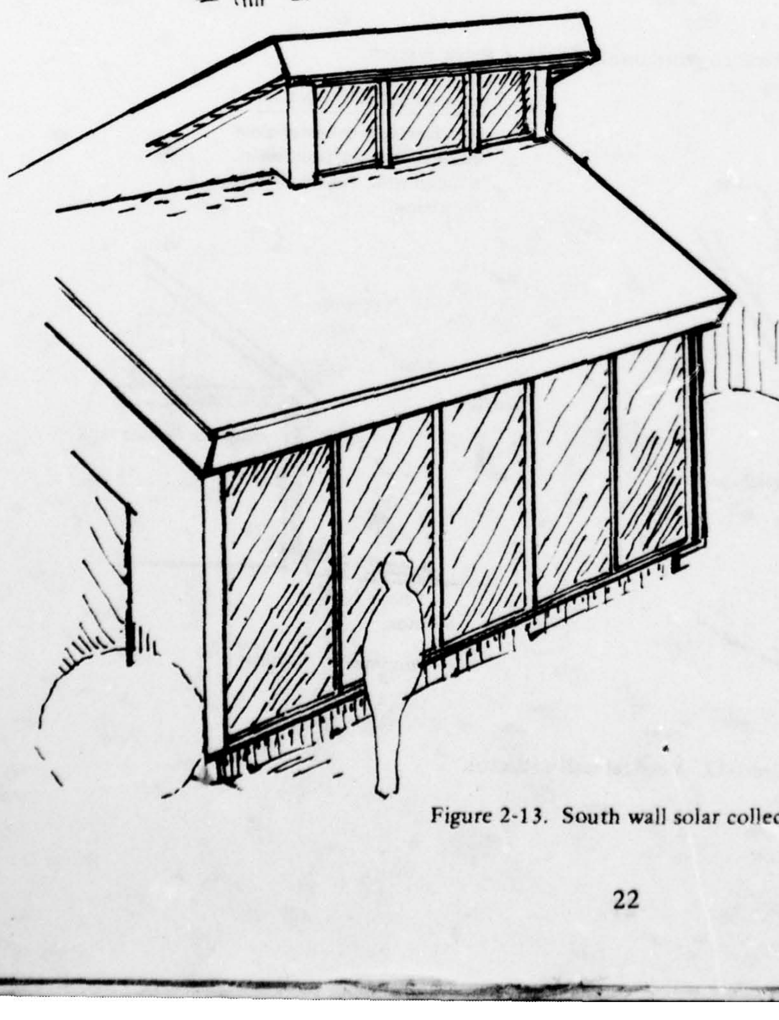


Figure 2-12. Vertical wall collector.





South Wall Collector With Combined Storage

Operation

- Rock storage is located directly behind collector
- Direct recirculation of air from collector to storage
- Collector is vertical
- Conventional hot air heater
  - Takes suction on storage. During normal solar operation, hot air from storage would be blown into house duct distrib. system. When storage temp. is too low, heater will come on to take over heating load.
- Limited summer cooling can be obtained by circ. cool night air through rock bed

Advantages

- Minimizes heat loss from the air moving between storage and collector by eliminating duct runs
- Reduces cost of construction by incorporating both collector and storage as structural elements in the house

Problems

- Some loss of efficiency by use of a vertical collector
- Potential shading problem from nearby trees or structures

Figure 2-13. South wall solar collector.

Retro Fit With Large Rock Storage

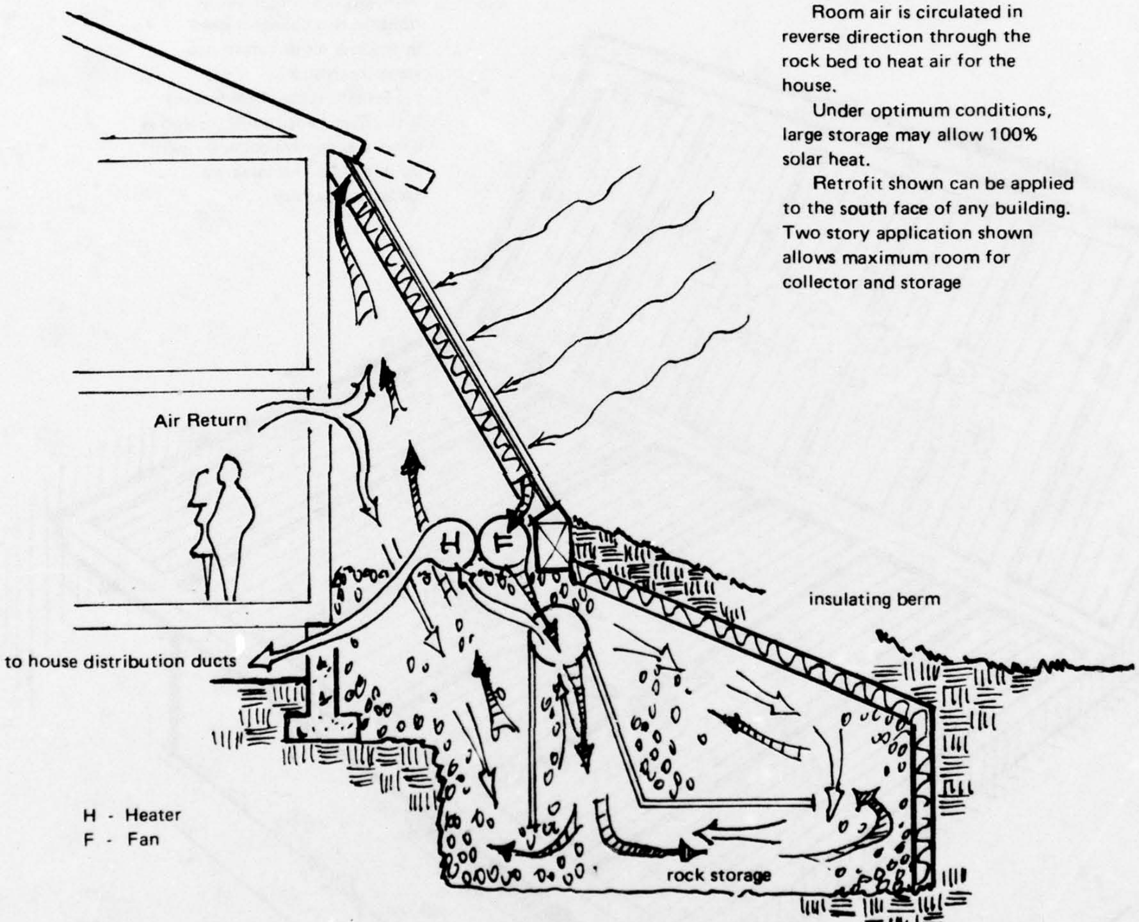
Operation

Hot air from collector is circulated through large rock storage under insulating berm.

Room air is circulated in reverse direction through the rock bed to heat air for the house.

Under optimum conditions, large storage may allow 100% solar heat.

Retrofit shown can be applied to the south face of any building. Two story application shown allows maximum room for collector and storage



Problems

Solar water heating would require a second heat exchanger at extra expense.

Ground position of collector may be shaded by trees or buildings.

High water table would interfere with storage.

Large amounts of rock may be expensive at some building sites.

Advantages

Excavation and backfill over the rock provides a low cost, well insulated containment for storage.

Figure 2-14. Retrofit with large rock storage.

Multistage Solar Collector

Operation

Solar hot air or hot water collectors are used in series with low cost single glaze nonselective collector used in the low temperature first stage (preheater).

Second stage (final heater) is the high temp. collector and is a more expensive collector with double glaze and selective collecting surface

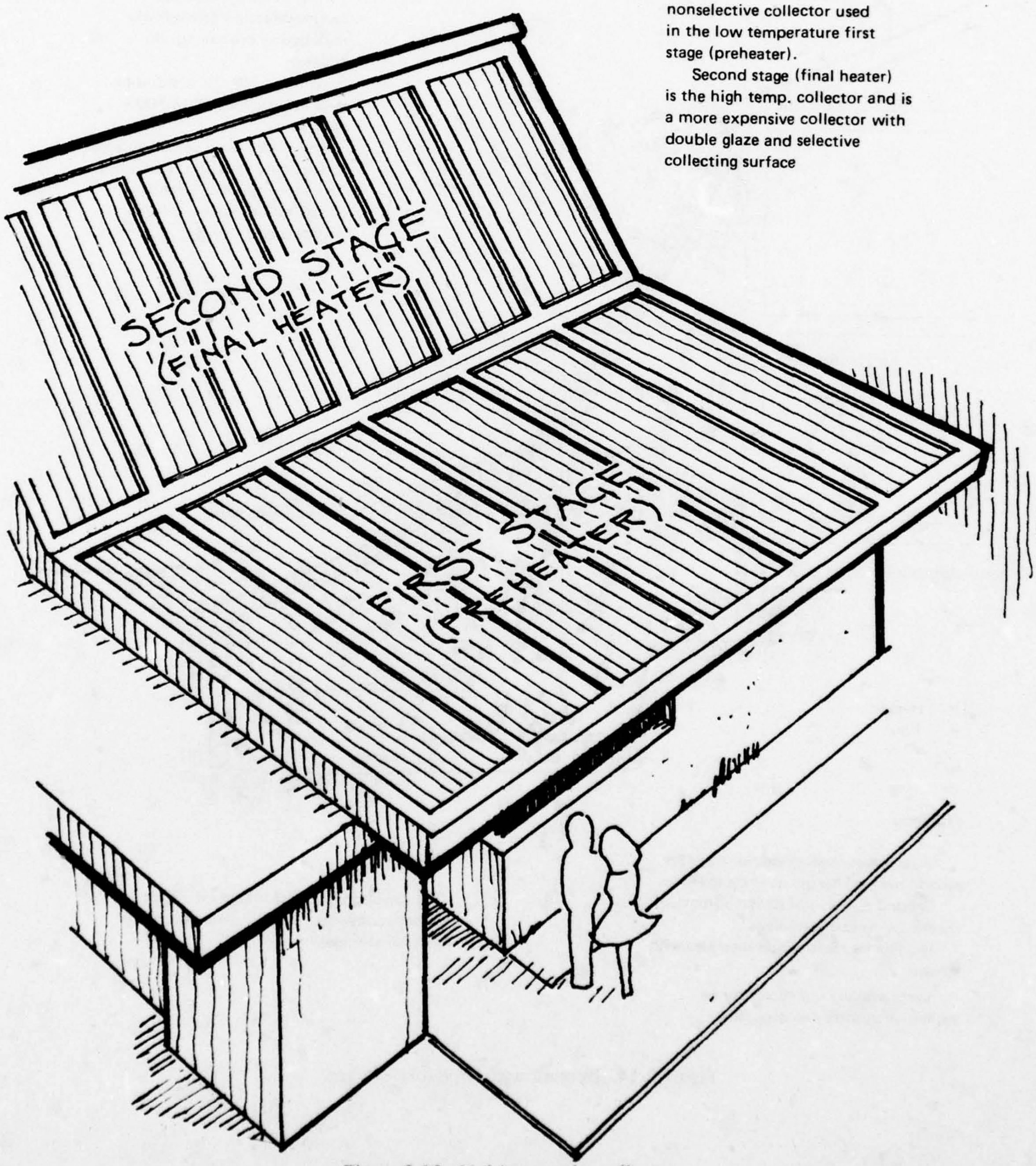


Figure 2-15. Multistage solar collector.

life expectancy. Pumps will have longer life if they are placed in low temperature parts of the water circuits than if handling hot water. Valves should be electrically operated and located out of the weather or well protected. A vent must be provided at the high point in liquid systems to eliminate entrapped air and it should also serve as a vacuum breaker to allow draining of the system. Systems should be piped to avoid having more than one high point, to avoid multiple venting.

3.0 DESIGN METHODS. There are three steps in the design of a solar system: determination of solar energy available per unit area of collector, determination of heating load, and sizing the collector for cost effectiveness. A series of worksheets (Section 3.13) has been prepared to facilitate the design process for liquid systems; see Section 3.12 for air systems. The worksheets should be duplicated as needed. The design method presented here is based substantially on the systems analysis done at the University of Wisconsin, Madison [4]. The complex interaction between the components of a solar heating system has been reduced by means of computer simulation to a single parametric chart of F_I A_C versus F_L A_C with f as parameter (Figure 3-1), where F_I is a function of a solar insolation and building heating load, A_C is collector area, F_L is a function of solar collector heat losses and building heating load, and f is the fraction of *build-heating* load supplied by solar heating. The requirement for pre-knowledge of system temperatures has been eliminated by use of these heat balance ratios.

The method has been checked with computer simulations for the climates of Madison, Wisconsin; Blue Hill, Massachussetts; Charleston, South Carolina; Albuquerque, New Mexico; and Boulder, Colorado. The standard errors of the differences between the computer simulated and estimated values (by this method) of $\bar{f}$ for the five locations were no greater than 0.014 (1.4% error); $\bar{f}$ is the yearly average of the monthly f. Eight years of data were used for the Madison, Wisconsin, case. This method, then appears to be sufficiently accurate for most applications.

3.1 JOB SUMMARY – WORKSHEET A. Worksheet A is a summary sheet where the effect of collector size on savings-investment ratio (SIR) is shown. This is the final desired answer to the question of the design process: What size collector (and total system) gives greatest payback? If all SIRs are less than 1.0, then a solar system is not feasible for the application at the conditions used in the design. A period of 15 years' fuel saving is used in calculations per NAVFAC P-442 as lifetime for utilities. Solar systems can be designed to last at least 15 years. Computations completed on subsequent worksheets will be transferred to Worksheet A. Note that only the portion of conventional heating systems cost in excess of that normally required should be included in solar systems cost analysis. However, for budgetary purposes in new construction, then, the total solar system cost is the sum of the excess cost plus the previously excluded conventional system cost.

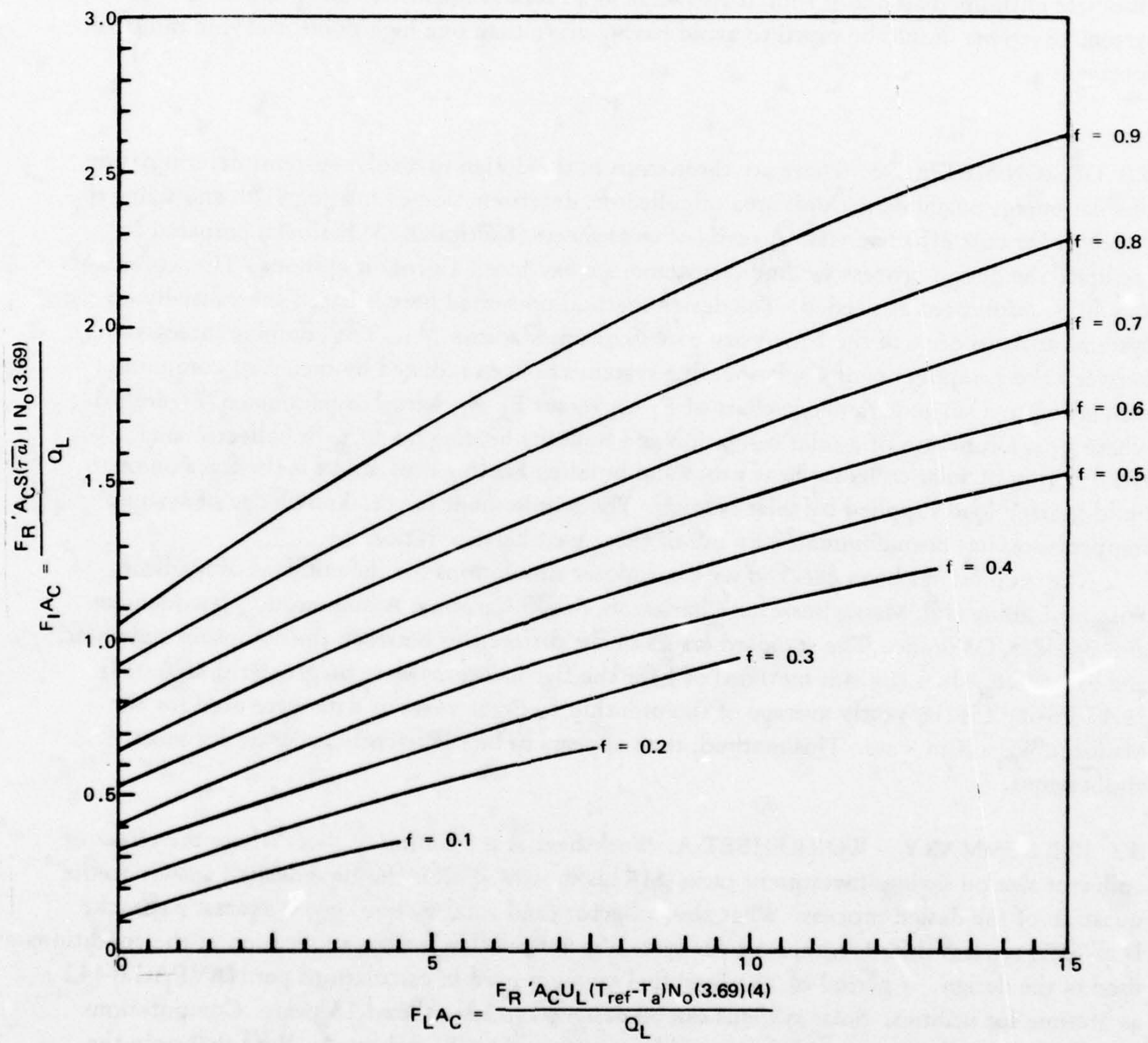


Figure 3-1. Fraction of heating/DHW load supplied by solar energy. (Reference 4)

3.2 SOLAR COLLECTOR PARAMETERS – WORKSHEET B. The purpose of Worksheet B is to gather the variables needed to calculate F_I and F_L (see paragraph 3.0). The first two parameters, $F_R\ (\tau\alpha)_n$ and $F_R\ U_L$ represent the y intercept and slope, respectively, of the η versus $\Delta T/I$ curve, Figure 2-2, applicable to the chosen collector. F_R is collector heat removal factor, τ is transmissivity of cover glazes, α is absorptivity of collector plate, U_L is overall collector heat loss coefficient. If η versus $\Delta T/I$ curve is not available, the $F_R(\tau\alpha)_n$ and $F_R\ U_L$ can be calculated; Reference 3 is recommended as a guide for this procedure. The slope will be a constant if the η versus $\Delta T/I$ curve is a straight line; however, if it is not a straight line, the slope to be used is the tangent to the curve in the expected range of $\Delta T/I$. The units of $F_R\ U_L$ must be Langleys/F-day for use on subsequent worksheets.

The term $(\dot{m}\,C_p)_c/A_c$ is the unit heat capacity flow rate of working fluid through the collector, where $\dot{m}$ is flow of working fluid through the collector, in lbm/hr, and C_p is specific heat of fluid in Btu/lbm F. The larger the flow rate, the lower will be the ΔT through collector and thus the higher will be the collector efficiency. A practical limit is reached at an $(\dot{m}\,C_p)_c/A_c$ of 10 Btu/hr ft^2 F, so the design procedure is based on values of this order of magnitude. The latter figure may be taken as constant in calculating subsequent parameters.

The value for ϵ_c, effectiveness of the collector – tank heat exchanger, is based on manufacturer's data for the conditions of flow through the heat exchanger. If no heat exchanger is employed between the collector and the tank, then this term equals 1.0. Such a heat exchanger might be employed if the working fluid were expensive, to reduce the amount of fluid required, or if it were desired to separate working fluid from potable water in a hot water storage tank.

The term $(\dot{m}\,C_p)_c/(\dot{m}\,C_p)_{min}$ is the ratio of the heat capacity flow rates in the collector – tank heat exchanger. The subscript "c" refers to the collector flow stream; the subscript min refers to whichever of the two flow rates has the lesser value.

The ratio F'_R/F_R, line 6, Worksheet B, where F'_R is collector – tank heat exchanger efficiency factor is calculated from the equation

$$\frac{F'_R}{F_R} = \left\{1 + \left[F_R\,U_L\left(\frac{A_c}{(\dot{m}\,C_p)_c}\right)\right]\left[\frac{(\dot{m}\,C_p)_c}{\epsilon_c(\dot{m}\,C_p)_{min}} - 1\right]\right\}^{-1}$$

using the factors previously developed. If there is to be no heat exchanger, then this ratio equals 1.0.

The next factor, $(\overline{\tau\alpha})/(\tau\alpha)_n$, line 7 Worksheet B, where the bar refers to an average value of $(\tau\alpha)$ and subscript "n" refers to the value of $(\tau\alpha)$ taken with the sun normal to the collector, may be taken as a constant: 0.92. This factor accounts for the reduction in transmission of insolation at high angles of incidence (early morning and late afternoon). In the final two parameters on Worksheet B, corrections for heat exchanger effectiveness (ϵ_c) and off-angle solar collection are made to the basic measured parameters to result in $F'_R\ (\overline{\tau\alpha})$ and $F'_R\ U_L$, which will be used in Worksheet D-1.

3.3 LOAD CALCULATIONS – WORKSHEET C-1. Worksheet C-1 is an aid to calculating the space heating and domestic hot water load for family housing. For other buildings use conventional methods of calculating load; computer programs are available for this. For existing buildings, heating load may be inferred from fuel bills, if available, see Example 1 (Section 4.1); or the Btu/ft^2 degree-day (dd) method of Worksheet C-1 may be used. Table 3-1 gives estimated Btu/ft^2 dd heat loss rates for various structural types used in family housing. If net heat loss rate is based on amount of fuel used, load is gross load and must be multiplied by furnace efficiency to get net heating load. Hot water usage is calculated on Worksheet C-2 (See Section 3.4) and transferred to Worksheet C-1. Net DHW use is desired; if gross figure based on fuel usage is the starting point, then it must be multiplied by heater efficiency to get net DHW. Utilization efficiency rather than an equipment efficiency should be used (see DM-3). Total net heating load is sum of space and DHW loads.

3.4 DEMAND CALCULATIONS – DHW – WORKSHEET C-2. Worksheet C-2 summarizes DHW demand determined by conventional methods: manual DM-3, chapter 1. Net DHW, $Q_d \times N_o$. (Q_d is Btu/day hot water demand) is transferred to column (W), Worksheet C-1, if a combined space heating DHW system is being designed. If hot water demand is calculated from fuel bills, a gross figure is obtained, which is entered in column (U), Worksheet C-1, and net = gross x η_w , where η_w = heater utilization efficiency.

Table 3-1. Building Heat Loss Rates

Construction	Net Loss Coefficient (Btu/ft^2 degree day)
A. Brick veneer, 4-bedroom house, asphalt roof, storm windows, no insulation, 15 mph wind	15.3
B. Same as A, but with 3-1/2-inch batts in walls and attic	9.3
C. Same as B, but with 6 inches insulation in attic	8.7
D. Same as B, but with 12 inches insulation in attic	8.4
E. Stucco over frame, 4-bedroom house, shake roof, 3-inch insulation in attic only	14.1
F. Frame, 3 bedroom, heated basement, 3-1/2-inch batts in walls, 5-1/2-inch batts in ceiling	11.7

3.5 MONTHLY SOLAR COLLECTION PARAMETERS – WORKSHEET D-1. Figures for Q_L, total heat load per month, are transferred to Worksheet D-1. Solar insolation, I, and slope factor, S, are obtained from Table 1-1 and Figure 3-2, respectively, for the location and latitude. If measured I for the location is available for several years, then the average of this data should be used. The slope factor corrects insolation data from the horizontal at which the insolation data

were taken, to the tilt angle of the collector. If the tilt angle is latitude plus 10 degrees, then Figure 3-2 may be used for S. For deviation from "latitude plus 10 degrees," see Reference 3. These calculations apply to south-facing collectors; no correction is needed for collectors facing up to 10 degrees east or west of south. The air temperature, T_a, is the average daily temperature taken from local records or the Climatic Atlas of the United States [5]. The factor ($T_{ref} - T_a$) accounts for the effects of ambient air temperature changes on collector heat losses. Then the parameters F_I and F_L may be calculated. Special care should be taken that units are consistent, so that F_I and F_L will have units of ft^{-2}. The factors (3.69) and (4.0) are necessary to achieve this. The factor (4.0) converts hours of sunlight per day (6) to hours per day (24).

3.6 FRACTION OF LOAD SUPPLIED BY SOLAR HEAT – WORKSHEET D-2. On Worksheet D-2, first select an area of solar collector for study, based on experience, similar design or arbitrary size (a collector area approximately one-half the floor area to be heated is a reasonable guess). Area is multiplied by F_I and F_L factors from Worksheet D-1 and the product is entered on Worksheet D-2. Then from Figure 3-1 pick off the values of f for each set of values of $A_c F_I$ and $A_c F_L$. Calculate average $\bar{f} = \Sigma Q_L f / \Sigma Q_L$. Then select other collector areas, larger or smaller, and repeat above procedure so that a trend may be observed in the following cost analysis calculations. Usually very sunny areas ($I > 500$ L/day) will have highest cost effectiveness at about $\bar{f} \approx 0.75$ and not so sunny areas ($I \approx 300$) at $\bar{f} \approx 0.50$. Storage volume on Worksheet D-2 may be sized by "rules of thumb" for minimum size. Minimum storage volumes are: one day's usage for DHW only and 1.0 gal/ft^2 (collector) for space heating and DHW. Up to 2.5 days' usage for DHW only has been recommended for family dwellings without auxiliary heat for DHW. Up to 5 gal/ft^2 has been recommended for space heating and DHW. The parametric chart (Figure 3-1) has been developed using storage equal to 1.8 gal of water/ft^2. Results will not be greatly affected by moderate deviations from this value. For liquids other than water the storage figures are modified by multiplying by the ratio of specific heats: C_p water/C_p liquid = 1.0/C_p liquid. Minimum weight of rocks for air system storage is 40 lb/ft^2 of collector; up to 75 lb/ft^2 has been used. If multiple cloudy days are a frequent occurrence, then more auxiliary heat will be used than was planned; the latter problem is relieved if larger storage is used. Consequently, if many cloudy days are expected, then the high end of the "rules of thumb" for storage sizing should be selected. The cost of energy storage may be calculated from Table 2-1, where, for the approximate size chosen, the various elements of tank order-of-magnitude cost are listed in terms of dollars/gallon. For instance, for an installed, 100 psi, lined steel tank, add the costs for unlined pressure tank, tank liner and installation. This figure is entered on Worksheet F. If the ultimate result of the analysis, Worksheet A, shows a cost effective system, then storage size can be increased from the minimum. Increased storage size saves fuel, and reduces the uncertainty in meeting the predicted $\bar{f}$ due to the approximate averaged method used here to calculate the heating load.

3.7 FUEL SAVINGS – WORKSHEET E-1. On Worksheet E-1, the value of the fuel saved by the solar heat collected is calculated for the several collector areas chosen.

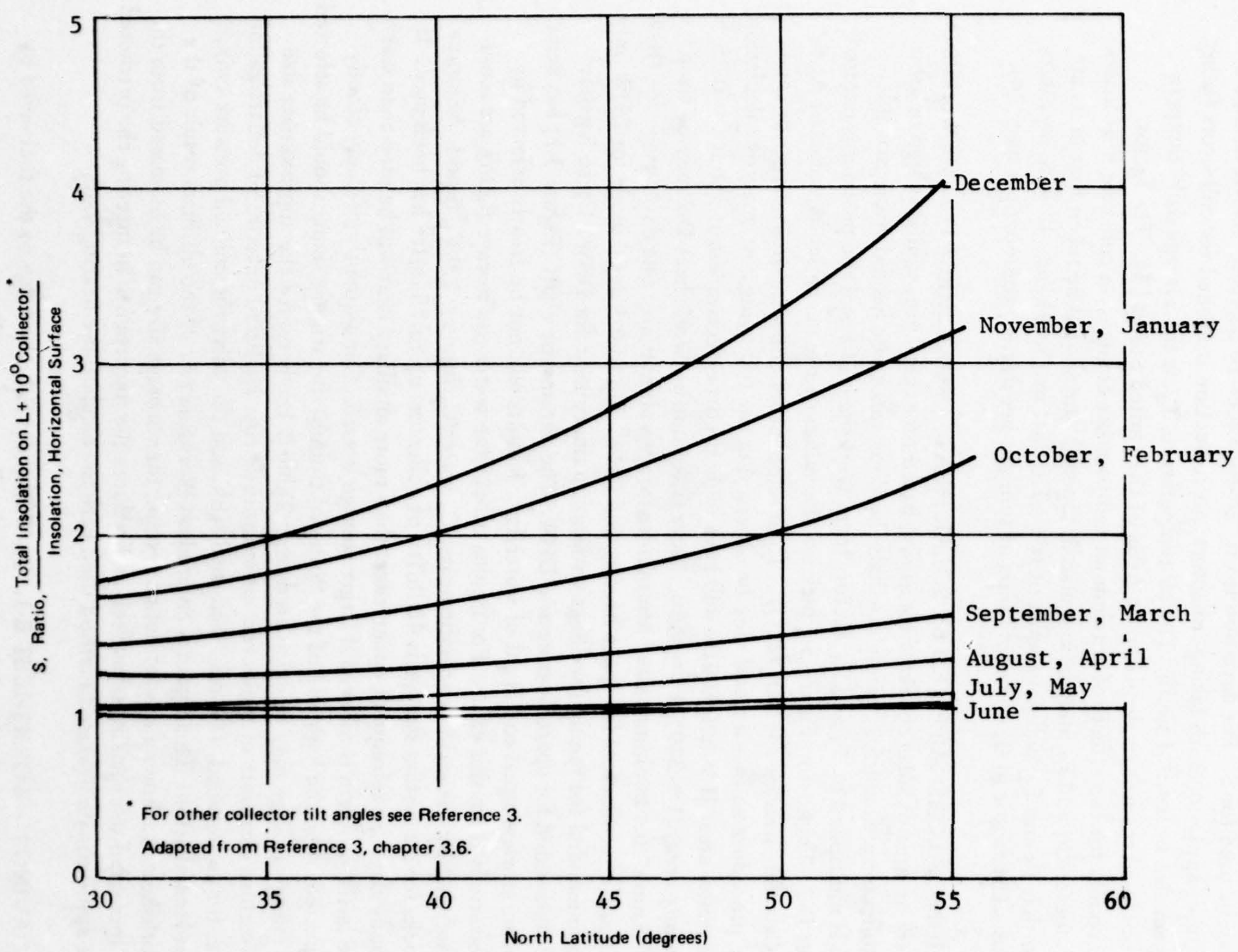


Figure 3-2. Slope factor, S, for use on Worksheet D-1 (average over one day).

$$\text{Value of fuel} = \frac{\bar{f} \times Q_{L_t} \times C_f}{\eta_w}$$

where $\bar{f}$ = yearly average fraction of heat load supplied by solar heat

Q_{L_t} = total yearly heating and DHW load (10^6 Btu)

C_F = cost of fuel in \$/10^6 Btu

η_w = utilization efficiency of space heater, DHW heater or an average efficiency in combined system

For the purpose of calculating \$/10^6 Btu, approximately:

Gas, one therm = 10^5 Btu

one MCF = 10^6 Btu

Oil, No. 2 = 140,000 Btu/gal: 5.84 x 10^6B/bbl

No. 5 = 150,000 Btu/gal: 6.3 x 10^6 B/bbl

Electricity,
1 kwh = 3,413 Btu

The present worth of 15 years' fuel saved may be calculated by using Worksheet E-2, or if standard fuel differential inflation rates (expected percentage increase/year in fuel prices above general inflation rate) and 10% discount factor are used, then a single multiplication given in note (2), Worksheet E-1 will give the answer. Current annual fuel inflation factors for use on Worksheet E-2 are given in Table 3-2. Refer to NAVFAC Instruction 4100.6 for latest fuel inflation factors to use. These figures then are transferred to Worksheet A, column (y). If a different fuel inflation rate than that in Table 3-2 is used, then Worksheet E-2 will facilitate calculations. A separate Worksheet E-2 must be completed for each collector area under study. The sum total of 15 years' fuel savings is then transferred to Worksheet A, column (y).

3.8 COLLECTOR TEMPERATURES – WORKSHEET E-1. Fluid temperature rise through collector is of interest and may be calculated from:

$$T_o - T_i = \frac{f\,Q_L/N_o}{C_p\,\theta\,G}$$

where T_o = collector outlet temperature

T_i = collector inlet temperature

G = flowrate in lbm/hr ft^2 collector (use 10.0 lbm/hr ft^2)

Q_L = heat load, Btu/mo (Worksheet C-1)

C_p = specific heat of fluid = 1. Btu/lbm F for water

θ = hours of useful sun in day (use 5 or 6 hours)

If a DHW only system is used, then temperature rise may be added to ground water temperature to obtain actual collector outlet temperature. For space heating/DHW systems, the minimum collector outlet temperatures will be the temperature of the water returning from the room heat exchanger plus the temperature rise through the collector. In general, the storage tank bottom temperature is added to temperature rise to obtain actual collector outlet temperature.

Table 3-2. Annual Fuel Inflation Factors

(Compound amount factors — factor B in present worth analysis, worksheet E-2.)

Example Year	Coal & Gas		Oil		Electric	
	7% Inflation 10% Discount		9% Inflation 10% Discount		3% Inflation 10% Discount	
	Single Amount	Cumulative Series	Single Amount	Cumulative Series	Single Amount	Cumulative Series
1	0.986	0.986	0.995	0.995	0.968	0.968
2	0.959	1.946	0.986	1.982	0.906	1.874
3	0.933	2.879	0.977	2.959	0.849	2.723
4	0.908	3.787	0.969	3.928	0.795	3.517
5	0.883	4.670	0.960	4.887	0.744	4.261
6	0.859	5.529	0.951	5.839	0.697	4.958
7	0.836	6.364	0.942	6.781	0.652	5.610
8	0.813	7.177	0.934	7.715	0.611	6.221
9	0.791	7.968	0.925	8.640	0.572	6.793
10	0.769	8.737	0.917	9.557	0.536	7.329
11	0.748	9.485	0.909	10.465	0.501	7.830
12	0.728	10.212	0.900	11.366	0.470	8.300
13	0.708	10.920	0.892	12.258	0.440	8.739
14	0.688	11.608	0.884	13.142	0.412	9.151
15	0.670	12.278	0.876	14.018	0.386	9.536

Notes: 1. Consult NAVFAC INSTR 4100.6 for latest fuel inflation factors. Consult NAVFAC Manual P-442 for Compound Amount Factor tables for inflation rates not given here.

2. These fuel inflation factors are applied to costs which are anticipated to escalate at a rate i% faster than general price levels, where i is the fuel inflation factor.

3.9 SOLAR SYSTEM COST – WORKSHEET F. Worksheets F and G may be used to convert all costs of the solar installation into cost/ft^2 collector. Since costs can differ significantly for space heating/DHW compared to DHW only, two separate columns are shown. Recent manufacturers' data are best for computations, but Tables 3-3 and 3-4 may be used as representative prices (based on data of June 1975). Contractor profit is indicated as 35%; another figure may be used if warranted. Total system cost estimate is transferred to Worksheet A.

Table 3-3. Solar System Component Cost Estimates

Item	Space/DHW ($)	DHW ($)
Antifreeze	1.00/ft^2	1.00/ft^2
Pumps, pipe, controls, heat exchanger	2.00	2.25
Auxiliary heater,		
Gross amount	4.00/ft^2	1.00/ft^2
Less value of conventional system	(3.15)	(1.00)
Auxiliary heater, net	0.85/ft^2 net	0/ft^2 net

Table 3-4. Solar Collector Prices[a]

Type	Unit Selling Price ($/sq ft)
Plastic, no cover	1.75
Aluminum and copper single glaze	5.00
Aluminum, double glazed (Mfgr. A)	4.50
Copper, double glazed	7.00-8.00
Copper, single glazed (Mfgr. B)	6.50-9.00
Galvanized iron, single glaze free flow	1.50 (mat. only) 3.00-4.00
Plastic, no glaze with insulation	4.00
Aluminum, double glazed (Mfgr. C)	5.07
Aluminum, no glaze	3.19
Galvanized iron, no glaze	2.86
Aluminum, double glazed (Mfgr. D)	5.85
Single glaze, copper (Mfgr. E)	6.50

[a] June 1975.

3.10 ADDITIONAL COSTS – WORKSHEET G. Worksheet G is a convenient checklist to collect costs associated with converting to solar energy. On new building designs, good insulation, weatherstripping, etc., will be called for to save energy, even if solar heating is not adopted, thus the solar system should not be burdened with these costs in new buildings. Costs are summed and divided by collector area, then cost is transferred to Worksheet F. Maintenance cost can vary from 1% of total systems cost in large installations to 5% in single residence DHW applications.

3.11 SIZING THE HEAT EXCHANGER FOR SPACE HEATING. According to Reference 4:

"The dimensionless parameter $\epsilon_L C_{min}/UA$, has been found to provide a measure of the size heat exchanger needed to supply solar heat to a specified building. For values of $\epsilon_L C_{min}/UA$ less than 1.0, the reduction in system performance due to too small a heat exchanger will be appreciable. Reasonable values of $\epsilon_L C_{min}/UA$ for solar space heating systems are between 1 and 3 when costs are considered. (This design method has been developed) with $\epsilon_L C_{min}/UA$ equal to 2.0."

C_{min} is heat capacity flowrate, which is the lesser of the two heat capacity flowrates in the load heat exchanger; ϵ_L is effectiveness of load heat exchanger and U A is overall heat loss coefficient of building times the building area.

◆ 3.12 AIR-HEATING COLLECTOR DESIGN. The design procedure for air systems (Reference 6) is very similar to that for liquid systems – the same worksheets may be used. Figure 3-3 gives the f-chart for this procedure. The procedure was developed using an air flow heat capacitance rate of 2.87 Btu/hr ft^2 F (about 156. SCF/hr ft^2). The performance of systems having collector capacitance rates between 1.47 and 5.87 Btu/hr ft^2 F can be estimated by multiplying the values of $F_L A_c\{[(\dot{m}c_p)_c/F_R A_c]/2.87\}^{0.28}$ (Reference 6). To calculate F_R see Reference 3, Section 7.7. The rock bed storage heat capacitance assumed was 19.6 Btu/ft^2 F. The performance of systems with other storage capacities can be determined by multiplying the dimensionless group $F_L A_c$ by $[(\rho V C_{p_r}/F_R A_c)/19.6]^{-0.3}$ (Reference 6). The standard deviation of the yearly $\bar{f}$ by this method from the computer simulated value was found to be 0.017 (Reference 6).

"A comparison of the f-charts for the liquid and air systems indicates that, for the same values of $[F_I A_c]$ and $[F_L A_c]$ the air system outperforms the liquid system particularly for systems designed to supply a large fraction of the heating load. [Some reasons for this behavior are:] the average collector fluid inlet temperature is lower for the air system (and thus the collector efficiency is higher) than that for the liquid system at times when . . . " room air is circulated through the collector and also because the more effective thermal stratification achieved in rock storage results in lower temperature air going to the collector. Also since no heat exchanger is required between collector and storage, that inefficiency is avoided. [Reference 6].

"It cannot be concluded, however, that air heating systems perform better than liquid systems. The overall collector efficiency factor, F_R, is ordinarily lower for air heaters. As a result $[F_I A_c]$ and $[F_L A_c]$ are ordinarily lower and thus the performance of an air system may be equivalent to or lower than that of a liquid system, all else being the same." (Reference 6)

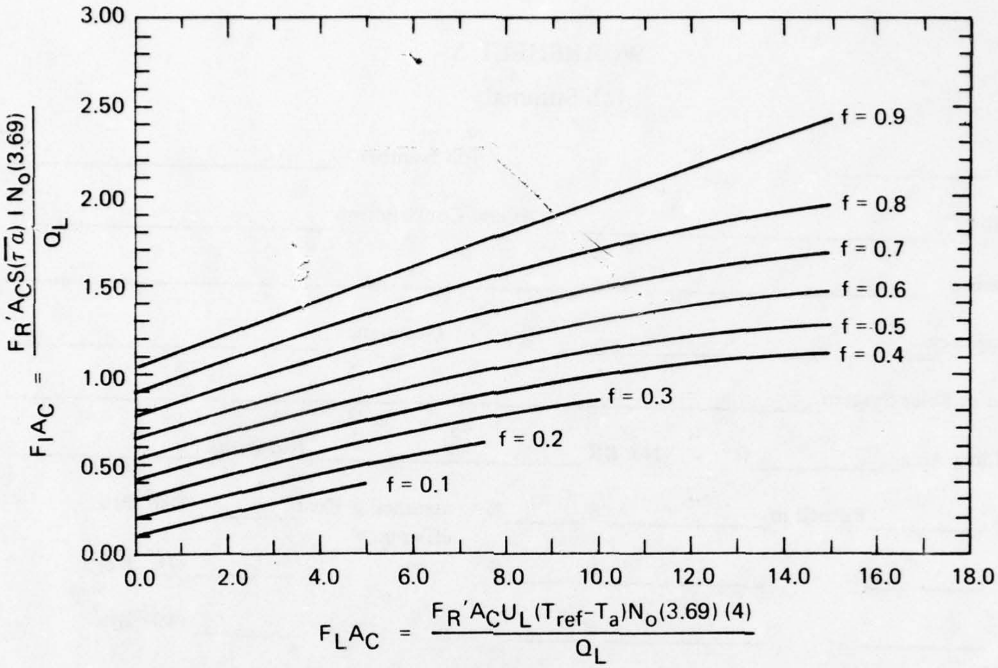


Figure 3-3. Fraction of heating/DHW load supplied by solar air heating system (after Reference 6).

3.13 WORKSHEETS

A	Job Summary
B	Solar Collector Parameters
C-1	Load Calculations
C-2	Demand Calculations – Domestic Water Heater
D-1	Monthly Solar Collection Parameters
D-2	Fraction of Load Supplied by Solar Heat
E-1	Value of Fuel Saved
E-2	Present Worth Analysis
F	Solar System Cost Analysis
G	Additional Cost Items Related to Use of Solar Heating
H	Deleted

WORKSHEET A

Job Summary

Date ____________ Job Number ____________________

Building ________________________ General Construction ____________________

Location ____

Occupancy ________________________ Hours of Occupancy ____________________

Type of Solar System ____

Building Area ____________ ft^2 No. BR ________________ No. Baths ____________

Fuel ________ Burned in ____________ @ ______ % assumed @ Cost ________ $/10^6$ Btu
efficiency

________ ____________ @ ______ % ________ $/10^6$ Btu

________ ____________ @ ______ % ________ $/10^6$ Btu

Solar Collector Description ____

Approx. Cost, installed, total system \$ __________ $/ft^2$ D.H.W.
(Worksheet F)

\$ __________ $/ft^2$ Space Heating/D.H.W.

(1)		(x)	(y)		
Area (From E-1)	$\overline{f}$ (From E-1)	Solar System Cost (From F)	Value of 15 yr. Fuel Saved (From E-1)	Savings/ Investment Ratio (y)/(x)	Payback Period (Table C, NAVFAC Manual P-442)

(1) From Worksheet E-1.

WORKSHEET B

SOLAR COLLECTOR PARAMETERS

JOB NO. ____________

(1) $F_R(\tau\alpha)_n =$ ________

(2) $F_R U_L =$ ________ Langleys/(°F day)

(3) $(\dot{m}C_p)_c / A_c =$ ________

(4) $\epsilon_c =$ ________

(5) $\dfrac{(\dot{m}C_p)_c}{(\dot{m}C_p)_{min}} =$ ________

(6) $\dfrac{F_R'}{F_R} = \left\{ 1 + \left[F_R U_L \left(\dfrac{A_c}{(\dot{m}C_p)_c} \right) \right] \left[\dfrac{(\dot{m}C_p)_c}{\epsilon_c (\dot{m}C_p)_{min}} - 1 \right] \right\}^{-1} =$ ________

(7) $\dfrac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} = \underline{0.92}$

$F_R' \overline{(\tau\alpha)} = \left(\dfrac{F_R'}{F_R} \right) \left(\dfrac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} \right) F_R(\tau\alpha)_n =$ ________

$F_R' U_L = \left(\dfrac{F_R'}{F_R} \right) F_R U_L =$ ________

(1) Obtained from y-intercept of η vs $\dfrac{\Delta T}{I}$ curve (Fig. 2-2 or manufacturer's data)

(2) Obtained from absolute value of slope of η vs $\dfrac{\Delta T}{I}$ curve. Units of Langleys/(°F day) are for a 6-hour sunlight day, not a 24-hour day. This must be observed when other units such as Btu/ft^2 °F hr are used.

(3) Mass flowrate of working fluid through collector, $\dot{m}$; specific heat of fluid C_p; area of collector, A_c

(4) Effectiveness of the collector-tank heat exchanger, if employed; if not employed, use $\epsilon_c = 1.0$.

(5) Ratio of heat capacity flowrate of the fluid through the collector to the heat capacity flowrate which is the minimum of the two fluids in the collector-tank heat exchanger, if employed. if not employed, use ratio = 1.0.

(6) Will equal 1.0 if no collector-tank heat exchanger employed.

(7) Use constant = 0.92 if no better data available.

WORKSHEET C-1

LOAD CALCULATIONS (5)

JOB NO.____________________

Heat Loss Rate (L)____________________ B/ft^2 degree-day gross (from Table 3-1) or net

Area (M)____________________ ft^2

Year: 19_____

Month	Degree Days (P)	GROSS Space Heat Load $R=(L)x(M)x(P)$	GROSS Hot Water (U)	NET Space Heat Load $(V)=(R x \eta w)$	NET Hot Water (W) $Q_d \times N_o$	NET Total $Q_L = (V)+(W)$
DEC						
JAN						
FEB						
MAR						
APR						
MAY						
JUN						
JUL						
AUG						
SEP						
OCT						
NOV						
	(1)	(2)	(3)	(4)	(3)	
					$\sum_{12} Q_L = Q_{L_t}$	

(1) From local records or Climatic Atlas of U.S., U.S. Dept. Commerce

(2) Based on fuel used.

(3) From Worksheet C-2, Gross = $\frac{\text{net}}{\eta_w}$, η_w = utilization efficiency of heater. May be approximated as constant.

(4) η_w = Utilization efficiency of heater. Net space heat may be calculated from heat loss of building or from fuel usage times efficiency of heater. If "L" is net heat loss rate, then "V" = LxMxP (without η_w).

(5) Units of heat on this Worksheet are in 10^6 Btu.

WORKSHEET C-2

DEMAND CALCULATIONS–DOMESTIC WATER HEATER

JOB NO. ______________

Type Building ______________________________ BR ______ Bath ______________

No. of Occupants ______________________________ Use/day-person(1) ______________

Average daily demand, gallons ________ x 8.3 lbs./gal. = ______________________ lbs. = W

Supply temperature (winter), ^{o}F ________ (2) Average water temperature (T_i)

After heating ______________ ^{o}F = Desired hot water temperature

Q_d = daily BTU's to be collected = $W\ C_p\ \Delta T = W\ C_p\ (T_o - T_i)$

________ lb. (1.0) ________ ^{o}F ______________________ B/day

Month	(3) Q_d, BTU's required one day	N_o No. of days in month	Net Monthly Average Demand $Q_d \times N_o$
DEC			
JAN			
FEB			
MAR			
APR			
MAY			
JUN			
JUL			
AUG			
SEP			
OCT			
NOV			
		$\Sigma Q_d N_o = Q_{d_t}$	

(1) Taken from Chapter 1, DM-3.

(2) Ground water temperature taken as normal daily average temperature from Climatic Atlas of US, US Department of Commerce (Reference 5)

(3) May be approximated as constant, or accuracy may be improved by using different T_i and T_o for each month.

WORKSHEET D-1

MONTHLY SOLAR COLLECTION PARAMETERS

JOB NO. ____________________

$F_R' \overline{(\tau\alpha)}$ = ______________ (from Worksheet B)

$F_R' U_L$ = ______________ (from Worksheet F)

Mo.	N_o (days/mo.)	(3) I (lys/day)	(4) S Slope Factor	Air Temp T_a (^oF)	$T_{ref}-T_a$ = (212F-Ta) (^oF)	(1) Q_L (10^6B/mo.)	(1,2) $F_I = \frac{N_o F_R' \overline{(\tau\alpha)} IS(3.69)}{Q_L}$ (ft^{-2})	(1,2,5) $F_L = \frac{F_R' U_L(T_{ref}-T_a)N_o(3.69)(4.0)}{Q_L}$ (ft^{-2})
DEC								
JAN								
FEB								
MAR								
APR								
MAY								
JUN								
JUL								
AUG								
SEP								
OCT								
NOV								

(1) Loads, Q_L, from Worksheet C-1

(2) Factor 3.69 converts langleys/day to BTU/ft^2 day.

(3) From Table 1-1 based on location: ____________________

(4) From Figure 3-2 based on tilt angle of latitude ________ + 10° = ________

(5) Factor(4.0) converts hours of sunlight (6 hours) to hours per day (24 hours).

WORKSHEET D-2

FRACTION OF LOAD SUPPLIED BY SOLAR HEAT

JOB NO. ____________________

Month	A_c = ________ ft^2			A_c = ________ ft^2			A_c = ________ ft^2		
	$A_c F_I$ (1)	$A_c F_L$ (1)	f (2)	$A_c F_I$	$A_c F_L$	f (2)	$A_c F_I$	$A_c F_L$	f (2)
DEC									
JAN									
FEB									
MAR									
APR									
MAY									
JUN									
JUL									
AUG									
SEP									
OCT									
NOV									
$\bar{f} = \frac{\Sigma Q_L f}{\Sigma Q_L}$									

Note: use Q_L's from Worksheet D-1.

STORAGE SIZING:

Minimum storage size - DHW one days' usage (Worksheet C-2) V = ____________ gal.

Space heat/DHW 1 gal/ft^2 collector V = 1 x A_c = ____________ gal.

For non-water, see section 3.6.

Other "rules of thumb" –

DHW 1.5 - 2.5 day's usage (the latter with no auxiliary heater) V = ____________ gal.

Space heat/DHW: 3-5 gal/ft^2 V = ______ x A_c ________ gal.

(1) F_I and F_L from Worksheet D-1

(2) From Figure 3-1 after A_cF_I and A_cF_L calculated.

WORKSHEET E-1

VALUE OF FUEL SAVED

JOB NO. ____________________

A_c Area From Worksheet D-2 (ft^2)	$\overline{f}$ Fraction Supplied by Solar	(3) Q_{L_t} (From Worksheet C-1) (BTU x 10^6/yr)	(1) Value of Fuel Saved per Year	(2) Present Worth of 15 yrs. Fuel at ____%/yr. Inflation Rate and 10% Discount Rate

(1) Value of fuel saved = $\dfrac{\overline{f} \times Q_{L_t} \times C_F}{\eta_W}$

C_F = cost of fuel, \$/10^6BTU

η_W = Utilization efficiency of furnace, DHW heater or compromise η_W. (Worksheet A)

(2) Present Worth = 12.278 x value of fuel saved/yr (gas/coal)
14.018 x value of fuel saved/yr (oil)
9.536 x value of fuel saved/yr (electric)

or use Worksheet E-2. Note: Consult NAVFAC Instr 4100.6 for latest fuel inflation rates.
Transfer figures to Worksheet A.

(3) Or Q_{d_t} from Worksheet C-2 for DHW only systems.

COLLECTOR TEMPERATURES

$$T_o - T_i = \frac{fQ_L/N_o}{GC_p\,\theta\,A_c} = \_\_\_\_\_\_\_\_\_\_\_\_$$

- Q_L from C-1 for month selected
- N_o number of days in month
- C_p specific heat of fluid
- θ number of hours of usable sun in day, use 5 or 6 hours
- G is flowrate in lbm/ft^2 hr, use (10 $lbm/hr\ ft^2$)

WORKSHEET E-2

PRESENT WORTH ANALYSIS

JOB NO. ____________

Collector Area ____________ ft^2

Year ____ (Specify CY or FY)	Year of Analysis	A Dollar Value of Fuel Saved in Zeroth Year (Worksheet E-1)**	B Fuel Inflation Factor @ ____ % Discount @ 10% From Table 3-2	C Annual Present Worth (A x B)
	Zeroth*			
	1st			
	2nd			
	3rd			
	4th			
	5th			
	6th			
	7th			
	8th			
	9th			
	10th			
	11th			
	12th			
	13th			
	14th			
	15th			

Present worth of fuel saved by system Σ ____________

* Year for which fuel costs are available if year of construction. Otherwise, escalate fuel costs to year of construction.

** Copy zeroth year fuel saved into each space in Column A.

WORKSHEET F

SOLAR SYSTEM COST ANALYSIS

JOB NO. ____________________

	Item Description	Area ______ ft^2 Space Heating/DHW	______ ft^2 DHW Only
(1)	Collector, installed	$/ft^2$	$/ft^2$
(2)	Storage tank, installed, ______________ \$______ /gal x ______ gal/ft^2 collector	$/ft^2$	$/ft^2$
(3)	Auxiliary heating unit, installed $cost/ft^2$ collector, net of conventional unit cost	$/ft^2$	$/ft^2$
(3)	Pumps, pipe, heat exchangers, controls $cost/ft^2$ collector	$/ft^2$	$/ft^2$
	Other (from Worksheet G)	$/ft^2$	$/ft^2$
	Subtotal	______	______
	Contractors profits, etc. @ 35%	$/ft^2$	$/ft^2$
(4)	TOTAL	______	______

	Area	$Cost/ft^2$	Cost
(4)			

(1) Manufacturer's data, or from Table 3-4, plus 20% for installation.

(2) See Table 2-1 and Worksheet D-2, plus $\$1/ft^2$ for antifreeze if applicable.

(3) See Table 3-3.

(4) Transfer totals to Worksheet A.

WORKSHEET G

ADDITIONAL COST ITEMS RELATED TO USE OF SOLAR HEATING

JOB NO. ______________________

COST ITEM (Capital costs this sheet)	ATTRIBUTED TO PLANNED SOLAR SYSTEM		
	Yes	No	Cost
Changes or add unit heaters			
Change or add circulating pumps			
Change or add controls, e.g., to radiators, attic exhaust fan			
Increase in interior floor space to accommodate tempering or storage tanks, pumps, etc.			
Excavation and backfill, storage tank			
Elimination of excess standby boilers, furnaces, etc.			
Capital value of space obtained by eliminating boilers, etc. in above item.			
Electricity for pumps, fans - excess cost over conventional system			
Maintenance @ 1%-5% of total system cost/year.			
Other			
Total			

Convert to $\$/ft^2$ collector:

$$\frac{\text{Total}}{A_c} = \_\_\_\_\_\_\_\_ ft^2$$

WORKSHEET H

SOLAR AIR COLLECTOR SYSTEM DESIGN SUMMARY

JOB NO. ____________________

			(1)	(3)	(2)	(2)
				USEFUL HEAT PRODUCED		
Month	Load Q_L B/mo. (from C-1)	Solar q_c B/mo. ft^2 (see Sec. 3.12)	Area - ft^2 $= \frac{Q_L}{q_c}$	$Q_u = A_c q_c$ B/mo. $A_c =$ ___	$Q_u = A_c q_c$ B/mo. $A_c =$ ___	$Q_u = A_c q_c$ B/mo. $A_c =$ ___
DEC						
JAN						
FEB						
MAR						
APR						
MAY						
JUN						
JUL						
AUG						
SEP						
OCT						
NOV						
Total Year			Totals/yr.			
			$\overline{f} = (\Sigma Q_u)/Q_{L_t}$			
				(3)	(3)	(3)

(1) Area $= \frac{Q_L}{q_c}$ where Q_L = heating load; q_c = solar heat collected/ft^2 collector.

(2) Subsequent columns of useful heat produced by lesser areas are provided to allow determination of value of lesser areas, if maximum cannot be justified.

*(3) In assigning values of useful heat, to the right of the double line, no more can be credited to the system for heat saving than the load can use. Enter the lesser of the two values, required or collected, for a given area. When Q_L is entered, identify the value with an asterisk (*).

4.0 EXAMPLE PROBLEMS

See Section 3 for instructions on preparing Worksheets

4.1 DISCUSSION OF EXAMPLE 1. Space and Water Heating System for Family Housing (See Section 4.1.1). Preliminary job data are entered on Worksheet A. The first step in the analysis (Worksheet B) is to determine the y-intercept and slope of the collector efficiency curve, Figure 2-2, curve 1b (2 glass, copper in aluminum sheet collector) which is reproduced in Figure 4-1. They are found to be 0.72 and 1.30 ly/day F, respectively. Next, the recommended figure of 10 B/ft^{2}F hr is selected for $(\dot{m}\, C_p)\, c/A_c$, line 3, Worksheet B. Since there will be no heat exchanger between collector and tank fluids, the next three factors equal 1. Then $F_R'\,(\tau\alpha)$ and $F_R'\,U_L$ are calculated and transferred to Worksheet D-1. The next step is to determine the heat load or demand. This is usually done by conventional methods of estimating heat losses from buildings and water usage per occupant. In Example 1, Worksheet C-1, the fuel usage was calculated using the Btu/ft^2 degree-day method. First, a rough estimate for the average family house at Port Hueneme was obtained from 1 month's usage of gas for all housing divided by the number of degree days in the month and the total number of square feet in the housing area. This figure (Q_L = 29.B/ft^{2}dd) included hot water heating. The estimated hot water use for a 3-bedroom, 2-bath home gave a figure for hot water use per square foot which was then subtracted from total use for the 1,500 ft^2 home. Resulting figure gave space heating fuel use as 21.5B/ft^{2}dd. This gross figure was multiplied by furnace efficiency of 0.7 to get 15.0 B/Ft^{2}dd net. Net heat is that which must be supplied by solar heat. Gross heat represents the heat value of fuel used by a conventional system. Worksheet C-2 is used to calculate DHW use. Enter on Worksheet D-1, the Q_L from Worksheet C-1. To complete Worksheet D-1, from Table 1-1 select the nearest, or most meterologically similar (same latitude and degree of cloudiness) location. Enter insolation in Langleys/day and slope factors from Figure 3-2 for the latitude of the location. Air temperature, T_a, is obtained from Reference 5 – average daily temperature. Worksheet D-2 is begun by selecting collector area of 200 ft^2 as an arbitrary size. Then 200 ft^2 was multiplied by F_I and F_L from Worksheet D-1. For each pair of points $A_c\, F_I$ and $A_c\, F_L$, Figure 3-1 is entered to find f. When $\bar{f}$, Worksheet D-2, average load carried by solar heating, is calculated, a result of 0.67 is obtained. Thus areas both larger and smaller were calculated and found to have $\bar{f}$ of 0.81 for 300 ft^2 and 0.87 for 100 ft^2 – the latter was considered for the DHW load only because the match is better between load and collector size. This information is transferred to and used on Worksheet E-1. Storage size is selected on the basis of one day's usage for DHW for the 100 ft^2 case, equal to 160 gallons. For the 200 ft^2 and 300 ft^2 cases, storage volumes of 200 gallons and 300 gallons, respectively, were selected. Use Worksheet E-1 to determine value of fuel saved. For the collector sizes and values of $\bar{f}$ from D-2 and the values of Q_{L_t}'s from C-1, calculate the value of fuel saved from the expression: $f\, Q_{L_t}\, C_f/\eta$. Assume fuel inflation rates of 7% for gas or coal, 9% for oil, 3% for electricity, a 10% discount rate on the present worth factor, and a 15-year amortization; then a single multiplying constant from note 2, Worksheet E-1, converts fuel saved/year to present value of 15 years fuel savings, and Worksheet E-2 is not used. Other inflation rate assumptions including nonuniform inflation rate over the life of the system require use of Worksheet E-2. Fluid temperature rise through the collector is calculated on Worksheet E-1 for a selected month.

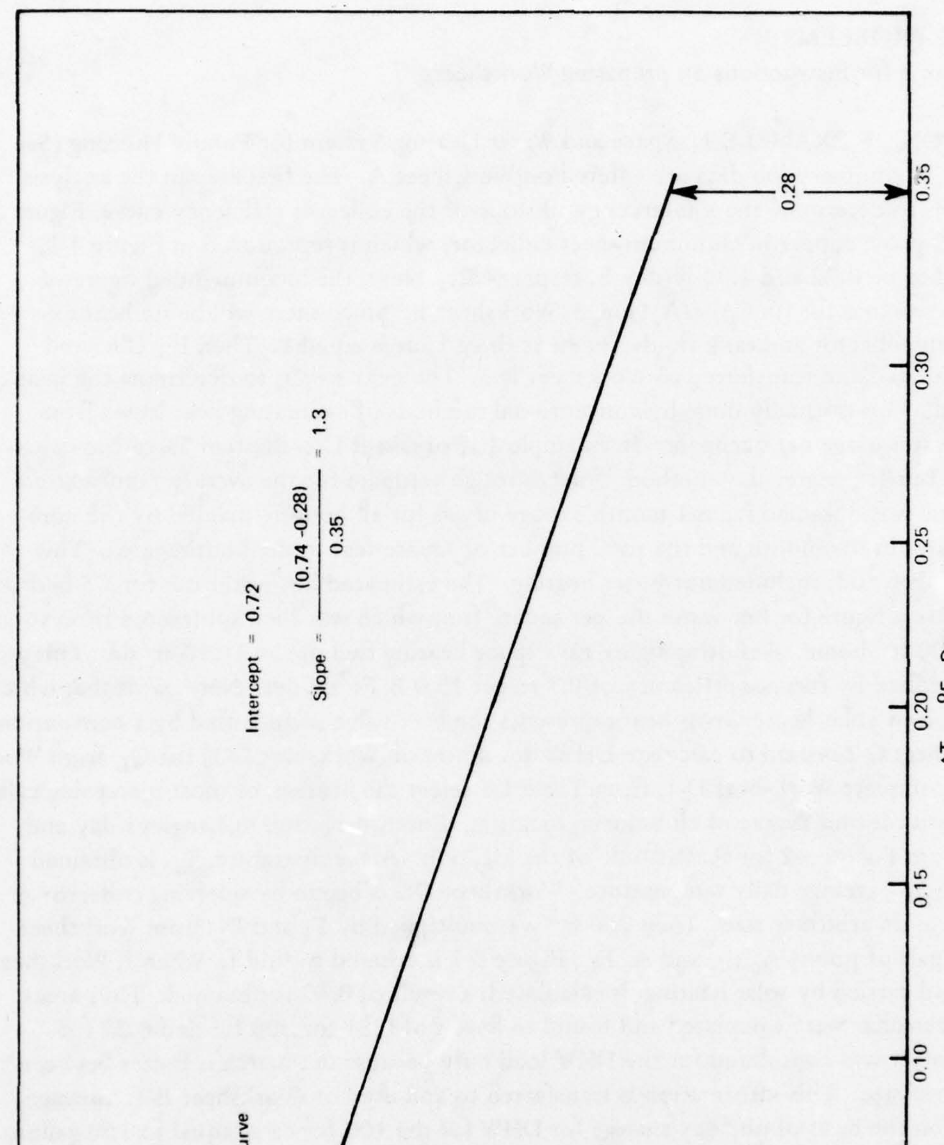


Figure 4-1. Collector efficiency curve for Example #1.

Calculation may be repeated for each month desired. For the month of December and 200 ft^2 collector area, f is 0.47, Q_L is 10.28 x 10^6 B/mo, G is 10 lb/hr ft^2. Using the formula on Worksheet E-1, a temperature rise of 13°F is found. This is the order of magnitude temperature rise most desired. Note that, using the same formula, the ΔT could be fixed at, say 10°F, and a flow rate, G, calculated. Sizing of pump, pipe, and collector tube diameters for low pressure drop is based on flowrate G. Worksheet F may be used to calculate total installed solar system cost/ft^2, or, the manufacturer's price for complete systems, installed, based on per square foot of collector area, may be used. On Worksheet F, collector cost may be obtained from Table 3-4 (current as of June 1975) or manufacturers' quote may be used. Tank volume is based on 1. gal/ft^2 collector for space heating/DHW or 1.6 gal/ft^2 collector for DHW only. The installed price of the insulated tank was taken from Table 2-1 (here $2.80/gal). Up to 5 gal/$ft^2$ may be specified for space heating/DHW. DHW-only storage may equal one or more days expected consumption. Other costs may be priced from a detailed design or figures from Table 3-3 may be used. Contractor's and salesman's profits and fees are estimated at 35% here. Other costs listed on Worksheet G are neglected for this example for simplicity. Returning to the table of Worksheet A, the values for area, solar system cost, etc., may be filled in. Note that in this example, the system would not pay off in 15 years at the assumed collector cost. This is due to the relative low cost of natural gas at this location (about 60% of the price of an equivalent heating value of No. 5 oil) and the relatively high calculated value of heat loss (B/ft^2dd) of the building. Usually the heat loss of the building can be halved for much less cost than half the price of the solar heating system. Thus, it is more cost effective to "super insulate" the building before designing the solar system.

4.1.1 EXAMPLE 1 – WORKSHEETS

WORKSHEET A

Job Summary

Date June 1975 Job Number Example 1

Building Family quarters General Construction Stucco

Location Port Hueneme, California

Occupancy Family of 4 Hours of Occupancy 24 hours

Type of Solar System Space and DHW

Building Area 1,467 ft^2 No. BR 3 No. Baths 2

Fuel Gas Burned in Heater @ 70 % assumed @ Cost $1.10 /10^6 Btu
efficiency

Gas DHW @ 60 % 1.10 /10^6 Btu

___ ___ @ ___ % ___ /10^6 Btu

Solar Collector Description 2 glass, copper in aluminum sheet, 4 inch insulation

Approx. Cost, installed, total system $ 22.42 /ft^2 D.H.W.
(Worksheet F)

$ 20.59 /ft^2 Space Heating/D.H.W.

(1)		(x)	(y)		
Area (From E-1)	$\overline{f}$ (From E-1)	Solar System Cost (From F)	Value of 15 yr. Fuel Saved (From E-1)	Savings/ Investment Ratio (y)/(x)	Payback Period (Table C, NAVFAC Manual P-442)
300	0.81	6,177	$1,351	0.22	N/A
200	0.67	4,200	1,118	0.27	N/A
100	0.87 DHW only	2,242	773	0.34	N/A

(1) From Worksheet E-1.

WORKSHEET B

SOLAR COLLECTOR PARAMETERS

JOB NO. Example 1

(1) $F_R(\tau\alpha)_n =$ .72

(2) $F_R U_L =$ 1.300 Langleys/(°F day)

(3) $(\dot{m}C_p)_c / A_c =$ 10 B/ft²F hr

(4) $\epsilon_c =$ 1.0

(5) $\dfrac{(\dot{m}C_p)_c}{(\dot{m}C_p)_{min}} =$ 1.0

(6) $$\frac{F_R'}{F_R} = \left\{ 1 + \left[F_R U_L \left(\frac{A_c}{(\dot{m}C_p)_c} \right) \right] \left[\frac{(\dot{m}C_p)_c}{\epsilon_c(\dot{m}C_p)_{min}} - 1 \right] \right\}^{-1} = 1.0$$

(7) $\dfrac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} =$ .95

$$F_R' \overline{(\tau\alpha)} = \left(\frac{F_R'}{F_R}\right) \left(\frac{\overline{(\tau\alpha)}}{(\tau\alpha)_n}\right) F_R(\tau\alpha)_n = 0.684$$

$$F_R' U_L = \left(\frac{F_R'}{F_R}\right) F_R U_L = 1.300$$

(1) Obtained from y-intercept of η vs $\dfrac{\Delta T}{I}$ curve (Fig. 2-2 or manufacturer's data)

(2) Obtained from absolute value of slope of η vs $\dfrac{\Delta T}{I}$ curve.

(3) Mass flowrate of working fluid through collector, $\dot{m}$; specific heat of fluid C_p; area of collector, A_c

(4) Effectiveness of the collector-tank heat exchanger, if employed; if not employed, use $\epsilon_c = 1.0$.

(5) Ratio of heat capacity flowrate of the fluid through the collector to the heat capacity flowrate which is the minimum of the two fluids in the collector-tank heat exchanger, if employed; if not employed, use ratio = 1.0.

(6) Will equal 1.0 if no collector-tank heat exchanger employed.

(7) Use constant = 0.95 if no better data available.

WORKSHEET C-1

LOAD CALCULATIONS (5)

JOB NO. Example 1

Heat Loss Rate (L) 15 B/ft^2 degree-day gross (from Table 3-1) or net

Area (M) 1,467 ft^2

Year: 19 74-75

Month	Degree Days (P)	GROSS Space Heat Load R=(L)x(M)x(P)	GROSS Hot Water (U)	NET Space Heat Load (V)=(R x ηw)	NET Hot Water (W) $Q_d \times N_o$	NET Total Q_L = (V)+(W)
DEC	318		5.48	6.99	3.29	10.28
JAN	309		5.48	6.80	3.29	10.09
FEB	322		5.48	7.09	3.29	10.38
MAR	312		5.48	6.86	3.29	10.15
APR	299		5.48	6.58	3.29	9.76
MAY	184		5.48	4.05	3.29	7.34
JUN	74		5.48	1.63	3.29	4.92
JUL	18		5.48	.40	3.29	3.69
AUG	6		5.48	.13	3.29	3.42
SEP	30		5.48	.66	3.29	3.95
OCT	87		5.48	1.91	3.29	5.2
NOV	182		5.48	4.00	3.29	7.29
	(1)	(2)	(3)	(4)	(3)	
					$\sum_{12} Q_L = Q_{L_t}$	86.47

(1) From local records or Climatic Atlas of U.S., U.S. Dept. Commerce

(2) Based on fuel used.

(3) From Worksheet C-2, Gross = $\frac{\text{net}}{\eta_w}$, η_w = utilization efficiency of heater. May be approximated as constant.

(4) η_w = Utilization efficiency of heater. Net space heat may be calculated from heat loss of building or from fuel usage times efficiency of heater. If "L" is net heat loss rate, then "V" = LxMxP (without η_w).

(5) Units of heat on this Worksheet are in 10^6 Btu.

WORKSHEET C-2

DEMAND CALCULATIONS–DOMESTIC WATER HEATER

JOB NO. Example 1

Type Building Quarters BR 3 Bath 2

No. of Occupants 4 Use/day-person(1) 40

Average daily demand, gallons 160 x 8.3 lbs./gal. = 1,328 lbs. = W

Supply temperature (winter), ^{o}F 40 (2) Average water temperature (T_i)

After heating 120 ^{o}F = Desired hot water temperature

Q_d = daily BTU's to be collected = $W\ C_p\ \Delta T = W\ C_p\ (T_o - T_i)$

1,328 lb. (1.0) 80 ^{o}F = 1.06×10^5 B/day

Month	(3) Q_d, BTU's required one day	N_o No. of days in month	Net Monthly Average Demand $Q_d \times N_o$
DEC	1.06×10^5	31	3.28×10^6
JAN	1.06×10^5	31	3.28×10^6
FEB	1.06×10^5	28	2.97×10^6
MAR	1.06×10^5	31	3.29×10^6
APR	1.06×10^5	30	3.18×10^6
MAY	1.06×10^5	31	3.29×10^6
JUN	1.06×10^5	30	3.18×10^6
JUL	1.06×10^5	31	3.29×10^6
AUG	1.06×10^5	31	3.29×10^6
SEP	1.06×10^5	30	3.18×10^6
OCT	1.06×10^5	31	3.29×10^6
NOV	1.06×10^5	30	3.18×10^6
		$\Sigma Q_d N_o = Q_{d_t}$	

(1) Taken from Chapter 1, DM-3.

(2) Ground water temperature taken as normal daily average temperature from Climatic Atlas of US, US Department of Commerce (Reference 5)

(3) May be approximated as constant, or accuracy may be improved by using different T_i and T_o for each month.

WORKSHEET D-1

MONTHLY SOLAR COLLECTION PARAMETERS

JOB NO. Example 1

$F_R'(\overline{\tau\alpha})$ = 0.684 (from Worksheet B)

$F_R' U_L$ = 1.300 (from Worksheet B)

Mo.	(3) N_o (days/mo.)	I (lys/day)	(4) S Slope Factor	Air Temp T_a (^oF)	$T_{ref}-T_a$ = (212F-Ta) (^oF)	(1) Q_L (10^6B/mo.)	(1,2) $F_I = \frac{N_o F_R' (\overline{\tau\alpha}) I S (3.69)}{Q_L}$ (ft^{-2})	(1,2,5) $F_L = \frac{F_R' U_L (T_{ref}-T_a) N_o (3.69)(4.0)}{Q_L}$ (ft^{-2})
DEC	31	228	1.9	55	167	10.28	0.003297	0.009084
JAN	31	243	1.7	50	162	10.09	0.003203	0.009550
FEB	28	337	1.4	50	162	10.38	0.003212	0.008385
MAR	31	446	1.2	55	157	10.15	0.004126	0.0092
APR	30	518	1.1	55	157	9.76	0.004420	0.00926
MAY	31	571	1.0	60	152	7.34	0.006087	0.01232
JUN	30	594	1.0	65	147	4.92	0.009142	0.01721
JUL	31	645	1.0	70	142	3.69	0.01368	0.02290
AUG	31	579	1.1	70	142	3.42	0.01457	0.02471
SEP	30	505	1.2	70	142	3.95	0.01162	0.0207
OCT	31	365	1.4	60	152	5.2	0.00769	0.0174
NOV	30	277	1.7	55	157	7.29	0.00489	0.01240

(1) Loads, Q_L, from Worksheet C-1

(2) Factor 3.69 converts langleys/day to BTU/ft^2 day.

(3) From Table 1-1 based on location: Los Angeles

(4) From Figure 3-2 based on tilt angle of latitude 34^o + 10° = 44^o

(5) Factor (4.0) converts hours of sunlight (6 hours) to hours per day (24 hours).

WORKSHEET D-2

FRACTION OF LOAD SUPPLIED BY SOLAR HEAT

JOB NO. Example 1

Month	A_c = 200 ft^2			A_c = 300 ft^2			A_c = 100 ft^2 DHW only Q_L = 3.29 x 10^6/mo.		
	$A_c F_I$ (1)	$A_c F_L$ (1)	f (2)	$A_c F_I$	$A_c F_L$	f (2)	$A_c F_I$	$A_c F_L$	f (2)
DEC	.659	1.816	.47	.99	2.72	.56	1.031	2.84	.68
JAN	.641	1.91	.45	.96	2.87	.63	.981	2.93	.63
FEB	.642	1.67	.46	.96	2.52	.64	1.012	2.65	.68
MAR	.825	1.84	.61	1.23	2.76	.81	1.271	2.34	.83
APR	.884	1.85	.64	1.32	2.78	.85	1.391	2.75	.85
MAY	1.218	2.46	.82	1.82	3.69	1.0	1.361	2.74	.87
JUN	1.83	3.44	1.0	2.74	5.16	1.0	1.366	2.57	.88
JUL	2.74	4.58	1.0	4.10	6.87	1.0	1.54	2.57	.97
AUG	2.91	4.94	1.0	4.37	7.41	1.0	1.52	2.57	.96
SEP	2.32	4.14	1.0	3.49	6.21	1.0	1.39	2.49	.9
OCT	1.54	3.48	.92	2.30	5.22	1.0	1.22	2.75	.8
NOV	.978	2.48	.67	1.47	3.72	.86	1.083	2.75	.72
		$\bar{f} = \frac{\Sigma Q_L f}{\Sigma Q_L}$	.67			.81			.87 DHW only

Note: use Q_L's from Worksheet D-1.

STORAGE SIZING:

Minimum storage size - DHW one days' usage (Worksheet C-2) V = 160 gal.

Space heat/DHW 1 gal/ft^2 collector V = 1 x A_c = 300/200 gal.

For non-water, see section 3.6.

Other "rules of thumb" –

DHW 1.5 - 2.5 day's usage (the latter with no auxiliary heater) V = ______ gal.

Space heat/DHW: 3-5 gal/ft^2 V = ______ x A_c ______ gal.

(1) F_I and F_L from Worksheet D-1

(2) From Figure 3-1 after A_cF_I and A_cF_L calculated.

WORKSHEET E-1

VALUE OF FUEL SAVED

JOB NO. Example 1

A_c Area From Worksheet D-2 (ft^2)	$\bar{f}$ Fraction Supplied by Solar	Q_{L_t} (From Worksheet C-1) (BTU x 10^6/yr)	(1) Value of Fuel Saved per Year	(2) Present Worth of 15 yrs. Fuel at 7 %/yr. Inflation Rate and 10% Discount Rate
300	.81	86.47	$110.06	$1,351.32
200	.67	86.47	91.04	1,117.79
100	.87	39.48	62.97	773.15

(1) Value of fuel saved = $\dfrac{\bar{f} \times Q_{L_t} \times C_F}{\eta_w}$

C_F = cost of fuel, $/$10^6$BTU

η_w = Utilization efficiency of furnace, DHW heater or compromise η_w. (Worksheet A)

(2) Present Worth = 12.278 x value of fuel saved/yr (gas/coal)
14.018 x value of fuel saved/yr (oil)
9.536 x value of fuel saved/yr (electric)

or use Worksheet E-2. Note: Consult NAVFAC Instr 4100.6 for latest fuel inflation rates.

Transfer figures to Worksheet A.

(3) Or Q_{d_t} from Worksheet C-2 for DHW only systems.

COLLECTOR TEMPERATURES

$$T_o - T_i = \frac{fQ_L/N_o}{GC_p\,\theta\,A_c} = \frac{.47(10.28 \times 10^6)/31}{10\ \text{lbm/hr ft}^2\ 1.\ \text{B/lbmF}(6\ \text{hr})(200\ \text{ft}^2)} = \underline{12.9F}$$

Q_L from C-1 for month selected

N_o number of days in month

C_p specific heat of fluid

θ number of hours of usable sun in day, use 5 or 6 hours

G is flowrate in lbm/ft^2 hr, use (10 lbm/hr ft^2)

f is fraction of heating load supplied by solar heating

WORKSHEET F

SOLAR SYSTEM COST ANALYSIS

Example 1

JOB NO. ____________

Item Description	Area 300 ft^2 Space Heating/DHW	100 ft^2 DHW Only
(1) Collector, installed	9.60 $/ft^2$	9.60 $/ft^2$
(2) Storage tank, installed, insulated, unlined $ 2.80 /gal x 1 gal/ft^2 collector	2.80 $/ft^2$	5.76 $/ft^2$
(3) Auxiliary heating unit, installed cost/ft^2 collector, net of conventional unit cost	.85 $/ft^2$	0 $/ft^2$
(3) Pumps, pipe, heat exchangers controls, cost/ft^2 collector	2.00 $/ft^2$	1.25 $/ft^2$
Other (from Worksheet G)	0 $/ft^2$	0 $/ft^2$
Subtotal	15.25	$16.61
Contractors profits, etc. @ 35%	5.34 $/ft^2$	5.81 $/ft^2$
(4) TOTAL	20.59	22.42

(4)

Area	Cost/ft^2	Cost
300	$20.59	$6,177
200	21.00 est.	4,200
100	22.42	2,242

(1) Manufacturer's data, or from Table 3-4, plus 20% for installation.
(2) See Table 2-1 and Worksheet D-2, plus $1/$ft^2$ for antifreeze if applicable.
(3) See Table 3-3.
(4) Transfer totals to Worksheet A.

4.2 DISCUSSION OF EXAMPLE 2. DHW for Dental/Dispensary Building. This design is for a planned dispensary building in Florida. Due to the favorable climate, a one glass, copper tube in aluminum sheet water heating collector is selected. From Figure 2-2, curve 1a, the y-intercept $F_R (\tau\alpha)_n$ is 0.83 and the slope at $\Delta T/I = 0.05$ is 1.7 ly/F-day. Factor $(\dot{m}C_p)c/A_c$ will be the usual 10 lbm/hr ft^2. Freezing will be avoided by draining collector at night, so, no heat exchanger will be needed between collector and tank fluids. As a result factors ϵ_c, $(\dot{m}C_p)_c/(\dot{m}C_p)_{min}$ and F'_R/F_R are all equal to 1.0. Factor $(\overline{\tau\alpha})/(\tau\alpha)_n = 0.95$ is a constant, $F'_R (\tau\alpha)$, and $F'_R U_L$ are calculated to be 0.79 and 1.7, respectively. Worksheet C-1 is not needed in this example. The final temperature of water at point of use will be 140°F, but on Worksheet C-2 we choose 120°F, realizing some auxiliary fuel will be used to heat water to 140°F in part of the year. The collector is more efficient heating to 120°F, than to 140°F and if system shows cost effectiveness at 120°F, we can raise the design temperature. Ground water temperature (winter) T_i is from Climatic Atlas of U. S. (Reference 5) (daily average temperature). The DHW demand in this case, was taken from the building specifications, and was based on the number and type of fixtures in the building. The load per day, and then per month (approximated as constant) are calculated. On Worksheet D-1, $F'_R(\overline{\tau\alpha})$ and $F'_R U_L$ are copied from Worksheet B, and $Q_L = Q_d$ from Worksheet C-2.

Insolation, I, is based on Tallahassee, Florida, and obtained from Table 1-1. Slope factor, S, is based on latitude of 30 degrees + 10 degrees = 40 degrees, and is obtained from Figure 3-2. Air temperature, T_a, is obtained from Reference 5. Parameters F_I and F_L are then calculated. Areas for study were selected on the basis of similar design (2,277 ft^2), which resulted in a large fraction (0.92) being supplied by solar heat, so smaller areas were investigated: vis, 1,000 and 1,500 ft^2. Note that in those months where f = 1.0, the temperature of the water will probably go above 120°F, so less auxiliary fuel will be used to heat water to 140°F. This design could be optimized by increasing the water heating load in those months where f = 1.0 to reflect the 140°F design temperature. Savings are calculated from the equation

$$\text{Savings} = W N_1 C_p (140 - 120\text{ F}) \frac{Cf}{\eta}$$

where W is weight of water heated per day (from Worksheet C-2). To determine cost benefit, first determine the number of months that f = 1.0; in this example, 4 months, which equals 120 days; this equals N_1. The savings is calculated to be approximately \$127, therefore,

$$\text{Savings} = 28{,}800 \frac{\text{lb}}{\text{day}} (120 \text{ days})\, 1.0 (20\text{ F}) \frac{\$1.10}{10^6 (0.6)}$$

$$= \$126.72$$

This amount may be added to "value of fuel saved per year." This second iteration is enough to change the cost optimum size from 1,500 ft^2 to 2,277 ft^2 (see Worksheet A). Storage size is taken as 3,500 gallons, one days useage. Areas and $\bar{f}$'s along with $Q_{d_t} = Q_{L_t}$ from C-2 are carried to Worksheet E-1, where value of fuel saved and present worth of 15 years fuel saving are com-

puted. Since a uniform fuel inflation rate of 7% and 10% discount rate is used, the present worth factor is 12.278 times one year's fuel savings. Temperature rise through collector in December was calculated on Worksheet E-1 and found to be about 20F, which is a reasonable value. The December temperature rise required, about 80°F, is obtained by means of the water in the storage tank passing through the collector four times in the six hour sunny period per day. Pumping parameter, G, if equal to 10 lbm/hr ft^2, will size the pump to cause tank water to pass through collector four times per day in this example. Solar system cost analysis (Worksheet F) begins with collector cost from Table 3-4 plus 20% for installation. Storage is to be in a 3,500 gallon phenolic lined, unpressurized, insulated, installed tank. Picking cost elements from Table 2-1 (4,000 gallons) plus \$.10 for phenolic liner, we get cost of:

$$\frac{\$1.10}{\text{gal}}\left(\frac{3{,}500\ \text{gal}}{1{,}500\ \text{ft}^2}\right) = \frac{\$2.56}{\text{ft}^2}$$

for the 1,500 ft^2 case. The auxiliary water heater will be employed with or without solar heating, so its initial cost does not add to costs here. Miscellaneous costs for pumps, pipe, controls, etc., from Table 3-3 are \$2.25/ft^2. From Worksheet G we get \$7.70/ft^2 for storage tank building and system maintenance (for 1,000 ft^2 case, \$11.60/ft^2). Contractor profits of 35% are included. Cost is extended and carried to Worksheet A. Cost of building was estimated to be 300 ft^2 times \$26.60/ft^2 cost of construction. Maintenance is obtained by estimating 1% of solar system cost (\$24.00/ft^2 x 1,500 ft^2 x 1%). Present worth factor for 15 years maintenance at 10% interest and 3% labor escalation is about 10; which is then multiplied by one year's maintenance cost. On Worksheet A, enter area, $\bar{f}$, solar system cost, value of fuel saved, and compute SIR. Since SIR's are less than 1.0, system is not presently feasible. Cost of fuel will have to triple, approximately, or solar system cost will have to come down for system to pay.

The SIR's show a maximum at 1,500 ft^2 for first iteration on heating load, and a maximum at 2,277 ft^2 for the second iteration. The answer then is 2,27 / ft^2.

4.2.1 EXAMPLE 2 – WORKSHEETS

WORKSHEET A

Job Summary

Date June 1975 Job Number Example 2

Building Dental/Dispensary General Construction Stucco

Location Jacksonville, FL

Occupancy Transient Hours of Occupancy 0800-1700

Type of Solar System DHW

Building Area ______ ft^2 No. BR ______ No. Baths ______

Fuel Gas Burned in Boiler @ 60 % assumed efficiency @ Cost $1.10 $/10^6$ Btu

______ ______ @ ___ % ______ $/10^6$ Btu

______ ______ @ ___ % ______ $/10^6$ Btu

Solar Collector Description one glass, copper tube in aluminum sheet, water

Approx. Cost, installed, total system $ 24.99 $/ft^2$ D.H.W.
(Worksheet F)

$ ______ $/ft^2$ Space Heating/D.H.W.

(1)		(x)	(y)		
Area (From E-1)	$\bar{f}$ (From E-1)	Solar System Cost (From F)	Value of 15 yr. Fuel Saved (From E-1)	Savings/ Investment Ratio (y)/(x)	Payback Period (Table C, NAVFAC Manual P-442)
1,500	.80	$37,500	$13,518	.36	N/A
1,000	.59	29,200	9,970	.34	N/A
2,277	.92	45,426	15,556	.34	
2,277	.92*	45,426	17,115*	.37	

(1) From Worksheet E-1.

* Second iteration on load, see explanation in text.

WORKSHEET B

SOLAR COLLECTOR PARAMETERS

JOB NO. Example 2

(1) $F_R(\tau\alpha)_n =$ .83

(2) $F_R U_L =$ 1.7 Langleys/(°F day)

(3) $(\dot{m}C_p)_c / A_c =$ 10 lbm/hr ft^2

(4) $\epsilon_c =$ 1.0

(5) $\dfrac{(\dot{m}C_p)_c}{(\dot{m}C_p)_{min}} =$ 1.0

(6) $\dfrac{F_R'}{F_R} = \left\{ 1 + \left[F_R U_L \left(\dfrac{A_c}{(\dot{m}C_p)_c} \right) \right] \left[\dfrac{(\dot{m}C_p)_c}{\epsilon_c (\dot{m}C_p)_{min}} -1 \right] \right\}^{-1} =$ 1.0

(7) $\dfrac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} =$ .95

$F_R' \overline{(\tau\alpha)} = \left(\dfrac{F_R'}{F_R} \right) \left(\dfrac{\overline{(\tau\alpha)}}{(\tau\alpha)_n} \right) F_R(\tau\alpha)_n =$ .79

$F_R' U_L = \left(\dfrac{F_R'}{F_R} \right) F_R U_L =$ 1.7

(1) Obtained from y-intercept of η vs $\dfrac{\Delta T}{I}$ curve (Fig. 2-2 or manufacturer's data)

(2) Obtained from absolute value of slope of η vs $\dfrac{\Delta T}{I}$ curve.

(3) Mass flowrate of working fluid through collector, $\dot{m}$; specific heat of fluid C_p; area of collector, A_c.

(4) Effectiveness of the collector-tank heat exchanger, if employed; if not employed, use $\epsilon_c = 1.0$.

(5) Ratio of heat capacity flowrate of the fluid through the collector to the heat capacity flowrate which is the minimum of the two fluids in the collector-tank heat exchanger, if employed; if not employed, use ratio = 1.0.

(6) Will equal 1.0 if no collector-tank heat exchanger employed.

(7) Use constant = 0.95 if no better data available.

WORKSHEET C-2

DEMAND CALCULATIONS–DOMESTIC WATER HEATER

JOB NO. Example 2

Type Building ______ BR ______ Bath ______

No. of Occupants ______ Use/day-person(1) ______

Average daily demand, gallons 3,474 x 8.3 lbs./gal. = 28,800 lbs. = W

Supply temperature (winter), ^{o}F 50 (2) Average water temperature (T_i)

After heating 120 ^{o}F = Desired hot water temperature

Q_d = daily BTU's to be collected = $W\,C_p\,\Delta T = W\,C_p\,(T_o - T_i)$

28,800 lb. (1.0) 70 ^{o}F 2.02 x 10^6 B/day

Month	(3) Q_d, BTU's required one day	N_o No. of days in month	Net Monthly Average Demand $Q_d \times N_o$
DEC	2.02 x 10^6	31	62.6 x 10^6
JAN	2.02 x 10^6	31	62.6 x 10^6
FEB	2.02 x 10^6	28	62.6 x 10^6
MAR	2.02 x 10^6	31	62.6 x 10^6
APR	2.02 x 10^6	30	62.6 x 10^6
MAY	2.02 x 10^6	31	62.6 x 10^6
JUN	2.02 x 10^6	30	62.6 x 10^6
JUL	2.02 x 10^6	31	62.6 x 10^6
AUG	2.02 x 10^6	31	62.6 x 10^6
SEP	2.02 x 10^6	30	62.6 x 10^6
OCT	2.02 x 10^6	31	62.6 x 10^6
NOV	2.02 x 10^6	30	62.6 x 10^6
		$\Sigma Q_d N_o = Q_{d_t}$	751.2 x 10^6

(1) Taken from Chapter 1, DM-3.

(2) Ground water temperature taken as normal daily average temperature from Climatic Atlas of US, US Department of Commerce (Reference 5)

(3) May be approximated as constant, or accuracy may be improved by using different T_i and T_o for each month.

WORKSHEET D-1

MONTHLY SOLAR COLLECTION PARAMETERS

JOB NO. Example 2

$F_R' \overline{(\tau\alpha)}$ = .79 (from Worksheet B)

$F_R' U_L$ = 1.7 (from Worksheet B)

Mo.	N_o (days/mo.)	(3) I (lys/day)	(4) S Slope Factor	Air Temp T_a (°F)	$T_{ref}-T_a$ = (212F-Ta) (°F)	(1) Q_L (10^6B/mo.)	(1,2) $F_I = \frac{N_o F_R' \overline{(\tau\alpha)} IS(3.69)}{Q_L}$ (ft^{-2})	(1,2,5) $F_L = \frac{F_R' U_L (T_{ref}-T_a) N_o (3.69)(4.0)}{Q_L}$ (ft^{-2})
DEC	31	260	1.8	55	157	62.6 x 10^6	.000675	.001950
JAN	31	274	1.7	55	157	62.6 x 10^6	.000672	.001950
FEB	28	311	1.4	55	157	62.6 x 10^6	.000568	.001900
MAR	31	423	1.2	60	152	62.6 x 10^6	.000733	.001889
APR	30	483	1.1	65	147	62.6 x 10^6	.000742	.001767
MAY	31	548	1.0	75	137	62.6 x 10^6	.000791	.001702
JUN	30	476	1.0	80	132	62.6 x 10^6	.000665	.001587
JUL	31	544	1.0	80	132	62.6 x 10^6	.000785	.001587
AUG	31	537	1.1	80	132	62.6 x 10^6	.000852	.001587
SEP	30	424	1.2	80	132	62.6 x 10^6	.000710	.001587
OCT	31	353	1.4	70	142	62.6 x 10^6	.000713	.001750
NOV	30	364	1.7	60	152	62.6 x 10^6	.000864	.001889

(1) Loads, Q_L, from Worksheet C-1

(2) Factor 3.69 converts langleys/day to BTU/ft^2 day.

(3) From Table 1-1 based on location: ______

(4) From Figure 3-2 based on tilt angle of latitude ______ + 10° = ______

(5) Factor(4.0) converts hours of sunlight (6 hours) to hours per day (24 hours).

WORKSHEET D-2

FRACTION OF LOAD SUPPLIED BY SOLAR HEAT

JOB NO. Example 2

Month	A_c = 1,000 ft^2			A_c = 1,500 ft^2			A_c = 2,277 ft^2		
	$A_c F_I$ (1)	$A_c F_L$ (1)	f (2)	$A_c F_I$	$A_c F_L$	f (2)	$A_c F_I$	$A_c F_L$	f (2)
DEC	0.675	1.95	0.48	1.01	2.92	.65	1.54	4.44	.86
JAN	0.672	1.95	0.48	1.01	2.92	.65	1.53	4.44	.86
FEB	0.568	1.90	0.40	.851	2.85	.56	1.29	4.42	.74
MAR	0.733	1.89	0.53	1.10	2.84	.72	1.67	4.41	.92
APR	0.742	1.77	0.55	1.11	2.65	.73	1.69	4.03	.94
MAY	0.791	1.70	0.58	1.19	2.65	.79	1.80	3.9	1.0
JUN	0.665	1.59	0.50	.998	2.38	.69	1.51	3.6	.9
JUL	0.785	1.59	0.59	1.18	2.38	.80	1.79	3.6	1.0
AUG	0.852	1.59	0.63	1.28	2.38	.84	1.94	3.6	1.0
SEP	0.710	1.59	0.53	1.07	2.38	.72	1.62	3.6	.93
OCT	0.713	1.75	.53	1.07	2.62	.72	1.62	4.03	.91
NOV	0.864	1.89	0.63	1.30	2.84	.84	1.97	4.4	1.0
$\bar{f} = \frac{\Sigma Q_L f}{\Sigma Q_L}$			.59			.80			.92

Note: use Q_L's from Worksheet D-1.

STORAGE SIZING:

Minimum storage size - DHW one days' usage (Worksheet C-2) V = 3,500 gal.

Space heat/DHW 1 gal/ft^2 collector V = 1 x A_c = ______ gal.

For non-water, see section 3.6.

Other "rules of thumb" –

DHW 1.5 - 2.5 day's usage (the latter with no auxiliary heater) V = ______ gal.

Space heat/DHW: 3-5 gal/ft^2 V = ______ x A_c ______ gal.

(1) F_I and F_L from Worksheet D-1

(2) From Figure 3-1 after A_cF_I and A_cF_L calculated.

WORKSHEET E-1

VALUE OF FUEL SAVED

JOB NO. Example 2

A_c Area From Worksheet D-2 (ft^2)	$\overline{f}$ Fraction Supplied by Solar	Q_{L_t} (From Worksheet C-1) (BTU x 10^6/yr) (3)	(1) Value of Fuel Saved per Year	(2) Present Worth of 15 yrs. Fuel at ____%/yr. Inflation Rate and 10% Discount Rate
1,500	0.80	751.2	$1,101	$13,518
1,000	0.59	751.2	812	9,970
2,277	0.92	751.2	1,267	15,556
2,277	0.92*	751.2+*	1,394	17,115

(1) Value of fuel saved = $\dfrac{\overline{f} \times Q_{L_t} \times C_F}{\eta_w}$

C_F = cost of fuel, $/$10^6$BTU

η_w = Utilization efficiency of furnace, DHW heater or compromise η_w. (Worksheet A)

(2) Present Worth = 12.278 x value of fuel saved/yr (gas/coal)
14.018 x value of fuel saved/yr (oil)
9.536 x value of fuel saved/yr (electric)

or use Worksheet E-2. Note: Consult NAVFAC Instr 4100.6 for latest fuel inflation rates.

Transfer figures to Worksheet A.

(3) Or Q_{J_t} from Worksheet C-2 for DHW only systems.

* Second iteration on load, see explanation in text (4.2)

COLLECTOR TEMPERATURES

$$T_o - T_i = \frac{fQ_L/N_o}{GC_p\,\theta\,A_c} = \frac{0.59(62.6 \times 10^6)/31}{(10)(1)(6)(1{,}000)} = 19.9F$$

Q_L from C-1 for month selected

N_o number of days in month

C_p specific heat of fluid

θ number of hours of usable sun in day, use 5 or 6 hours

G is flowrate in lbm/ft^2 hr, use (10 lbm/hr ft^2)

WORKSHEET F

SOLAR SYSTEM COST ANALYSIS

JOB NO. Example 2

	Item Description	Area ____ ft^2 Space Heating/DHW	1,500 ft^2 DHW Only
(1)	Collector, installed	/ft^2	$ 6.00/ft^2
(2)	Storage tank, installed, phenolic lined, nonpressure $ 1.10 /gal x ____ ~~gal/ft²~~ collector	3,500 gal. /ft^2	2.56/ft^2
(3)	Auxiliary heating unit, installed cost/ft^2 collector, net of conventional unit cost	/ft^2	0 /ft^2
(3)	Pumps, pipe, heat exchangers, controls cost/ft^2 collector	/ft^2	2.25/ft^2
	Other (from Worksheet G)	/ft^2	7.70/ft^2
	Subtotal		18.51
	Contractors profits, etc. @ 35%	/ft^2	6.48/ft^2
(4)	TOTAL		24.99

(4)

Area	Cost/ft^2	Cost
1,500	$24.99	$37,500
1,000	29.20	29,200
2,277	19.95	45,426

(1) Manufacturer's data, or from Table 3-4, plus 20% for installation.

(2) See Table 2-1 and Worksheet D-2, plus $1/$ft^2$ for antifreeze if applicable.

(3) See Table 3-3.

(4) Transfer totals to Worksheet A.

WORKSHEET G

ADDITIONAL COST ITEMS RELATED TO USE OF SOLAR HEATING

JOB NO. Example 2

COST ITEM (Capital costs this sheet)	ATTRIBUTED TO PLANNED SOLAR SYSTEM		
	Yes	No	Cost
Changes or add unit heaters		X	
Change or add circulating pumps		X	
Change or add controls, e.g., to radiators, attic exhaust fan		X	
Increase in interior floor space to accommodate tempering or storage tanks, pumps, etc.	X		$ 8,000
Excavation and backfill, storage tank		X	
Elimination of excess standby boilers, furnaces, etc.		X	
Capital value of space obtained by eliminating boilers, etc. in above item.		X	
Electricity for pumps, fans - excess cost over conventional system		X	
Maintenance @ 1%-5% of total system cost/yearly.	X		360/yr x 10 = 3,600
Other		X	
Total			$ 11,600

Convert to $/ft^2 collector:

$\frac{\text{Total}}{A_c}$ = $7.70 ft^2

5.0 DIRECTORY OF SOLAR EQUIPMENT MANUFACTURERS

5.1 SOLAR FLAT PLATE COLLECTOR MANUFACTURERS – (Domestic hot water/building space heating systems)

AAI Corporation – P. O. Box 6767, Baltimore, MD 21204 (Custom only)

American Solar Energy Corp. – 2960 Westwood St., Las Vegas, NV 89102

ASG Industries – P. O. Box 929, Kingsport, TN 37662

Askelon Metal Prod. – Tel Aviv, Israel (DHW)

Beasley Industries Pty. – Bolton Ave., Devon Park, S. A. 5008, Australia (DHW)

Beutel's Solar Heating Co. – 1527 North Miami Ave., Miami, FL 31136 (DHW)

Braemar Engineering Co. – 7 Jones St., O'Connor, W. A. 6163, Australia (DHW)

C&C Solarthermics, Inc., Box 144, Smithsburg, MD (ISC System)

CSI Solar Systems Division – 12400 49th St. North, St. Petersburgh, FL 33732

Corning Glass Works – Corning, N. Y. 14830

D&J Sheet Metal Co. – 10055 N. W. 7th Ave., Miami, FL 33150

Daylin, Inc. (Sunsource) – 9570 W. Pico Blvd, Los Angeles, CA 90035 (Thermosyphon DHW)

DuPont, EI – 1007 Market St, Wilmington, DE 19898 (Plastic glazes)

E&K Service Co. – 16824 74th Ave., N. E., Bothell, WA 98011

Ecotechnology– 234 Barbara Ave, Solana Beach, CA 92075

Edwards Engineering Co. – 101 Alexander Ave. Pompton Plains, N. J. 07444

Emerson Electric Co. – 8100 W. Florissant, St. Louis, MO 63136

Energex Corporation – 5115 Industrial Road, Suite No. 513, Las Vegas, NV 89118

Energy Systems, Inc. – 634 Crest Dr., El Cajon, CA 92021

Enthone Div., Am. Smelting and Refining Co. – P. O. Box 1900, West Haven, CT 06510

Environmental Designs – Div. of Steelcraft Corp., P. O. Box 12408, Memphis TN 38112

Fred Rice Productions, Inc. – 6313 Peach Ave., Van Nuys, CA 91401

Free Heat – P. O. Box 8934, Boston, MA 02114

Garden Way Labs – P. O. Box 66, Charlotte, VT 05445

General Electric – King of Prussia Park, P. O. Box 8661, Philadelphia, PA 19101

General Industries – 2238 Moffett Dr., Ft. Collins, CO 80521

Golden Investments LTD – 7701 Whitepine RI, Chesterfield, VA (ISC System)

Hadley Solar Energy Co. – P. O. Box 1456, Wilmington, DE 19899 (Drawings only)

Helio-Dynamics, Inc. – 518 South Van Ness Ave., Los Angeles, CA 90020

Heliotec, Inc. – 33 Edinboro St, Boston, MA 02160

Hitachi America Ltd. – 437 Madison Ave., New York, NY 10022

Hoflar Industries – 5511 128th St, Surrey, B. C., Canada

Honeywell Inc. – 2600 Ridgway Parkway, Minneapolis, MN 55413

ILSE Engineering – 7177 Arrowhead Rd, Duluth, MN 55811 (absorber plates)

International Solar Power Co., Ltd – 22B, Rosenkaeret, DK 2860, Soborg

International Solarthermics Corporation – P. O. Box 397, Nederland, CO 80466 (licences others to manufacture ISC System)

Inter Technology Corporation – P. O. Box 340, Warrenton, VA 22186 (custom only)

Libbey Owens Ford. 811 Madison Ave, Toledo, OH 43695

Itek Corp., Optical Systems Division – 10 Maguire Rd., Lexington, MA 02173

Kalwall Corp., Box 237, Manchester, N. H. 03105

K. McMillian Enterprises – 1 Tower Road, Newtown, TAS. 7008 Australia

Materials Consultant, Inc. – 2150 South Josephine St., Denver, CO 80202

Paul Mueller Co. – Box 828, Springfield, MO 65801 (heat transfer surfaces)

North American Solar-Dynamics, Inc., – 1700 Prudential Plaza, Denver, CO 80202 (ISC system)

Northrup Inc. – 302 Nichols Dr. Hutchins, TX 75141

Obelitz Industries Inc. – P. O. Box 2788, Seal Beach, CA 90740

Olin Corp., E. Alton, IL 52024 (absorber plates)

Optical Coating Laboratory, Inc., Box 1599 Santa Rosa, CA 95403 (coatings for absorbers and glass)

Owens-Illinois – P. O. Box 1035, Toledo OH 43666

People/Space Co. – 259 Marlboro St., Boston, MA 02109 (open channel type)

Physical Industries Corp. P. O. Box 357, Lakeside, CA 92040

Powell Brothers, Inc. – 5903 Firestone Blvd., Southgate, CA 90280

PPG Industries, Inc. – One Gateway Center, Pittsburgh, PA 15222

Rayosol – Carretera de Cadiz, 32 Torrmolinos (Malaga) Spain

Raypak, Inc. – 31111 Agoura Rd., Westlake Village, CA 91361

Revere Copper and Brass, Incorporated – P. O. Box 151, Rome, NY 13440

Reynolds, Inc. – P. O. Box 3069, Torrance, CA 90509

Reynolds Metals Co. – 6601 W. Broad St., Richmond, VA 23261

Rodgers & McDonald – 3003 N. E. 19th Dr., Gainsville, FL 32601

Rohm & Hass, Independence Mall W., Philadelphia, PA 19105 (plastic glazes)

Schultz Field Enterprises – LaJolla, CA 92036

Sekisui Kayaku Kogiyo Co. – 2 Kinugasa Machi, Osaka, Japan (DHW)

Shelley Radiant Ceiling Co. – 8110 St. Louis Ave., Skokie, IL 60076

Skytherm Processes & Engr. – 2424 Wilshire Blvd., Los Angeles, CA 90057

J&R Simmons Construction Co., Inc. – 2185 Sherwood Dr., South Daytona, FL 32019

Smalls Sola Heeta Co. – 10 Goongarrie St., Bayswater, W. A. 6063 Australia (DHW)

Solar-Aire – 1565 9th St., White Bear Lake, Minnesota (ISC system)

Solar Centre – 176 Ifield Rd., Chelsea, London, SW 10 9AF, England

Solar Collector, Inc – 61 Bernadette St., Westbrook ME 04092 (ISC system)

Solar Conversion Corporation of America – 16260 Raymer St., Van Nuys, CA 91406

Solar Corporation – 9620 Royalton Dr., Beverly Hills, CA 90210

Solar Energy Development, Inc. – 1437 Alameda Ave., Lakewood, OH 44107

Solar Energy Digest – P. O. Box 17776, San Diego, CA 92117

Solar Energy Engineering – 748 Big Tree Rd., S. Daytona, FL 32019

Solar Energy, Inc. – 171 Belmar Blvd., Avon Lake, OH 44012

Solar Energy Research Corp. – 10075 County Line Rd., Longmont, CO 80501

Solar Heat LTD – 99 Middleton Hall Rd., Kings Norton Birmingham, England (DHW)

Solar Heaters, Inc. – 3536 W. Peoria, Phoenix, AZ 85029

Solar Hot Water Systems – 34 Flinders Rd., Earlwood, N. S. W. 2006 Australia

Solar Manufacturing Co. – 10 Conneaut Lake Rd., Greenville, PA (ISC system)

Solar Power Corporation – 930 Clocktower Parkway, New Port Richey, FL 33552

Solar Power, Inc. – 75 Snyder St., Sharon, PA (ISC system)

Solar Products, Inc. – P. O. Box S2883, San Juan, PR 00903

Solar Stor – Parker, SD (ISC system)

Solar Systems Inc. – 323 Country Club Dr., Rehoboth Beach, DE 19971

Solar-Thermics Enterprises, LTD. Box 238, Creston, IA (ISC system)

Solar Water Heater Co., 10021 S. W. 38th Terrace, Miami, FL 31165

Solaray Corp. – 2414 Makiki Heights Dr., Honolulu, HI 96822 (DHW system)

Solaron Corporation – 4850 Olive St., Denver, CO 80022

Solar-Ray Appliances, Box 75, Tuart Hill, W. A., Australia (DHW)

Solarsystems – 1802 Dennis Dr., Tyler, TX 75701

Solerg Assoc. – Box 90691, Los Angeles, CA 90009 (imports concentrating collector)

Solergy – 150 Green St., San Francisco, CA 94111

Sol-R-Tech – The Trade Center, Hartford, VT 05047

Sol-Therm Corp. – 7 West 14th St., New York, NY 10011

State Stove&Mfg. Co., Inc. – Ashland City, TN 37015 (storage tanks)

Stolle Corp, The – 1501 Michigan St., Sidney, OH 45365

Sunburst, Inc. – 70 N. W. 94th St., Miami Shores, FL 33150

Sunglow, Inc. – 12500 W. Cedar. Lakewood, CO 80228 (ISC system)

Sunearth Construction Co., Inc – P. O. Box 99, Milford Square, PA 18935

Sunshine Energy Corporation – Route 25, Brookfield Center, CT 06805

Sunwater Company – 1112 Pioneer Way, El Cajon, CA 92020 (DHW)

Sunworks, Inc. – 669 Boston Post Rd., Guilford, CT 06437

S. W. Hart and Co. – G. P. O. Box X2311, Perth, WA 6001 Australia

The Solacyl Company – Wyvern House, Anchor Rd., Bristol BS 1 5 TT, England

The Stolle Corp. – 1501 Michigan St., Sidney, OH 45365

Thermax Electric Water Heaters Pty – P. O. Box 173, Hamilton Central, Q'LD, 4007 Australia

Thomason Solaris System – c/o Edmund Scientific Co., 150 Edscorp Bldg., Barrington, NJ 08007 (open channel type plans)

Tranter, Inc. – 735 E. Haxel St., Lansing, MI 48909 (absorber plates)

Turbon Engineering Pty LTD, Birudi St., Coorparoo, Australia (DHW)

Unitspan Arch. Systems, Inc. – 9419 Mason Ave., Chatsworth, CA 91311

U. S. Solar Corporation – 6407 Ager Road, West Hyattsville, MD 20781

Vincze, S. A., Paragon Chambers – Lambton Quay, Wellington, C. I., N. Z. (DHW)

W. R. Robbins & Sons – 1401 N. W. 20th Street, Miami, FL 33125

Ying Mfg. Corporation – 1940 W. 144th St., Gardena, CA 90249

Youngblood Co., Inc. – 1085 N. W. 36th St., Miami, FL 33142

Zomeworks Corp. – P. O. Box 712, Albuquerque, N. M. 87103 (passive systems)

5.2 SWIMMING POOL AND PORTABLE SYSTEMS

Basic Designs Inc. – 300 Bridge Way, Sausalito, CA 94965

Burke Rubber Company – 2250 So. Tenth St., San Jose, CA 95112

Fafco, Inc. – 138 Jefferson Dr., Menlo Park, CA 94025

Fun & Frolic, Inc. – Box 277, Madison Heights, MI 48071

LOF Bros. Solar Appliances – Box 10594, Denver, Co 80210

Raypak, Inc. – 31111 Agoura Road, Westlake Village, CA 91361

Solar Energy Applications, Inc. – 2200 E. Washington St., Phoenix, AZ 85034

Solar Energy Co. – Deerwood Dr., Merrimack, NH 03054

Solar Systems, Inc. – 7456 Valjean Ave., Van Nuys, CA 19406

Solar Systems Sales – 180 Country Club Dr. Novato, CA 94947

Suhay Enterprises – 1505 E. Windsor Dr., Glendale, CA 91205

The Sundu Company – 3319 Keys Lane, Anaheim, CA 92804

Sunwater Co. – 1112 Pioneer Way, El Cajon, CA 92020

U. S. Solar Pillow, Box 987, Tucumcari, NM 88401

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7.0 LIST OF SYMBOLS

A_c	Collector area (ft^2)
C_F	Cost of fuel ($\$/10^6$ Btu)
C_{min}	Lesser of the heat capacity flowrates in the space heating load heat exchanger
C_p	Specific heat of fluid (Btu/lbm°F)
f	Fraction of building load supplied by solar heating
$\bar{f}$	Average of f over one year
F_I	Solar design parameter for insolation (ft^{-2})
F_L	Solar design parameter for collector losses (ft^{-2})
F_R	Collector heat removal factor (¶ 3.2)
F'_R	Collector heat exchanger efficiency factor (¶ 3.2)
G	Flowrate through collector per unit area (lbm/hr ft^2)
I	Solar insolation (Langley/day)
$\dot{m}$	Mass flow through collector (lbm/hr)
$(\dot{m}\,C_p)_c$	Heat capacity flow rate through collector (Btu/hr°F)
$(\dot{m}\,C_p)_{min}$	The lesser of the two heat capacity flowrates in the collector-tank heat exchanger
N_o	Number of days in month
N_I	Number of days in computation period
q_c	Solar heat collected per ft^2 of collector per month (Btu/ft^2mo)
Q_d	DHW heating load (Btu/day)
Q_{d_t}	Yearly total load (DHW only) (Btu/yr)
Q_L	Total heat load (space + DHW) per month (Btu/mo)
Q_{L_t}	Yearly total heat load (Space + DHW) (Btu/yr)
Q_u	Useful heat collected = $A_c q_c$ (Btu/mo)
S	Slope factor = ratio of direct solar radiation on a tilted surface to that on a horizontal surface
T_a	Ambient air temperature (°F)

T_{avg}	$T_{avg} = (T_o + T_i)/2$ (^oF)
T_c	$T_c = T_{avg}$ Collector temperature (^oF)
T_i	Collector inlet fluid temperature (^oF)
T_o	Collector outlet fluid temperature (^oF)
T_{ref}	212^{o}F, a reference temperature
ΔT	$T_o - T_i$ (^oF)
UA	Overall heat loss coefficient of building times building area (Btu/hr^{o}F)
U_L	Collector overall heat loss coefficient (Langleys)/^{o}F-day)
W	Weight of DHW to be heated/day (lbm)
ϵ_c	Effectiveness of the collector-tank heat exchanger
ϵ_L	Effectiveness of the space heating load heat exchanger
η	Collector efficiency
η_w	Heater (DHW or space) utilization efficiency
θ	Hours of useful sun/day
$(\tau\alpha)$	Product of cover transmittance and plate absorptance accounting for dirt and shading
$(\overline{\tau\alpha})$	Average value of $(\tau\alpha)$ over one day
$(\tau\alpha)_n$	$(\tau\alpha)$ at normal radiation incidence
ϕ	Utilizability (¶ 3.12)

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The purpose of this document is to provide guidance in the design and cost analysis of solar heating systems for buildings and domestic hot water (DHW). The nature of solar radiation, several types of solar systems, storage devices, and architectural considerations are among topics included. Calculation methods are included for determining collector size, storage size, simplified building and DHW loads, value of fuel saved, and saving-investment ratios. The calculation procedure is based on parametric curves for fraction of heating load supplied

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20. Continued

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